THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

EFFICIENCY OF FLEXIBLE FIXTURES: DESIGN AND CONTROL

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ABSTRACT

The manufacturing industries have been using flexible production technologies to meet the demand for customisation. As a part of production, fixtures have remained limited to dedicated technologies, even though numerous flexible fixtures have been studied and proposed by both academia and industry. The integration of flexible fixtures has shown that such efforts did not yield the anticipated performance and resulted in inefficiencies of cost and time. The fundamental formulation of this thesis addresses this issue and aims to increase the efficiency of flexible fixtures.

To realise this aim, the research in this thesis poses three research questions. The first research question investigates the efficiency description of flexible fixtures in terms of the criteria. Relative to this, the second research question investigates the use of efficiency metrics to integrate efficiency criteria into a design procedure. Once the efficiency and design aspects have been established, the third research question investigates the active control of flexible fixtures to increase their efficiency.

The results of this thesis derive from the outcome of seven studies investigating the automotive and aerospace industries. The results that answer the first research question use five criteria to establish the efficiency of flexible fixtures. These are: fundamental, flexibility, cost, time and quality. By incorporating design characteristics in respect of production system paradigms, each criterion is elaborated upon using relevant sub-criteria and metrics. Moreover, a comparative design procedure is presented for the second research question and comprising four stages (including mechanical, control and software aspects). Initially, the design procedure proposes conceptual design and verification stages to determine the most promising flexible fixture for a target production system. By executing detailed design and verification, the design procedure enables a fixture designer to finalise the flexible fixture and determine its efficiency. Furthermore, a novel parallel kinematics machine is presented to demonstrate the applicability of the design procedure's analytical steps and illustrate how appropriate kinematic structures can facilitate the efficiency-orientated design of flexible fixtures.

Based on the correlation established by the controller software's design procedure, the active control of flexible fixtures directly affects the quality criterion of flexible fixture efficiency. This provides the answer to the third research question, on general control strategies for active control of flexible fixtures. The introduction of a system model and manipulator dynamics proposes force and position control strategies. It is shown that any flexible fixture using a kinematic class can be controlled, to regulate the force and position of a workpiece and ensure that process nominals are preserved. Moreover, using both direct and indirect force control strategies, a flexible fixture's role in active control can be expanded into a system of actively controlled fixtures that are useful in various processes. Finally, a position controller is presented which has the capacity to regulate both periodic and non-periodic signals. This controller uses an additional feedforward scheme (based on the Hilbert transform) in parallel with a feedback mechanism. Thus, the position controller enables flexible fixtures to regulate the position of a workpiece in respect of any kind of disturbance.

Keywords: flexible; fixture; efficiency; design; control; production; manufacturing; assembly.

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Ilker Erdem

APPENDED PUBLICATIONS

PUBLICATION A

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PUBLICATION B

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PUBLICATION C

I. Erdem, P. Helgosson, A. Gomes, and M. Engström, "Automated Flexible Tooling for Wing Box Assembly: Hexapod Development Study," in *SAE Technical Paper 2016-01-2110*, 2016.

PUBLICATION D

I. Erdem, C. Levandowski, C. Berlin, H. Kihlman, and J. Stahre, "A novel comparative design procedure for reconfigurable assembly fixtures," *CIRP Journal of Manufacturing Science and Technology*, vol. 19, pp. 93-105, 2017/11/01/ 2017.

PUBLICATION E

I. Erdem, G. Asbjörnsson, and H. Kihlman, "Feedforward control for oscillatory signal tracking using Hilbert transform," *European Journal of Control*, 2019/06/11/ 2019.

PUBLICATION F

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PUBLICATION G

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ADDITIONAL PUBLICATIONS

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A. Andersson, I. Erdem, P. Funk, H. Rahman, H. Kihlman, K. Bengtsson, et al., "Inline Process Control - a concept study of efficient in-line process control and process adjustment with respect to product geometry," presented at the SPS 2016, the 7th Swedish Production Symposium, 25 Oct 2016, Lund, Sweden, Lund, Sweden, 2016.

G. Asbjörnsson, I. Erdem, M. Evertsson, "Application of the Hilbert transform for diagnostic and control in crushing," *Mineral Engineering*, vol. 147, p. 106086, 2020/03/01/ 2020.

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LIST OF ABBREVIATIONS

AMS	agile manufacturing systems
AProC	automated process control BiW
ART	affordable reconfigurable tooling
BiW	body in white
CAFD	computer-aided fixture design
CNC	computer numerical control
DOF	degrees of freedom
DRM	design research methodology
FEA	finite element analysis
FFT	fast Fourier transform
FM	frequency modulated
FMS	flexible manufacturing systems
GT	group technology
HT	Hilbert transform
LOCOMACHS	low-cost manufacturing and assembly of composite and hybrid structures
MachOpt	machine optimisation learning
MPS	modular production systems
MTC	manufacturing technology centre
PKM	parallel kinematics machine
PLC	programmable logic controller
PMS	performance measurement systems
RMS	reconfigurable manufacturing systems
RQ	research question
SDF	systems development framework
SMED	single minute exchange of die(s)

I

INTRODUCTION

Understanding the dynamics of different constituents of a production system has been scrutinised so as to meet the increasing demand for responsive manufacturing. Spanning from operational activities to physical manufacturing, every part plays an integral role in the dynamics, where the nature of interaction is highly coupled. This enables changes in each constituent to start a chain reaction. As part of this relationship, fixtures have evolved and contributed to change. This chapter aims to introduce the dynamics from a fixturing point of view and present the essential parts of the research, namely its aim and research questions.

1.1 BACKGROUND

As a group of activities, realising a product involves a variety of operations, spanning from design and supply of materials to the physical manufacturing. Product realisation requires these activities to emerge hierarchically, so using a term which encompasses the hierarchical journey of product realisation lays the necessary foundation for defining the role of fixtures [1]. Based on this formulation of a hierarchical system, two terms have emerged and been used interchangeably: “production” and “manufacturing” systems [2]. To establish a map of items describing the dynamics, “production systems” is used as an overarching term in this thesis.

Since “production systems” is at the apex of the hierarchy, the system describing the physical activities has been called “manufacturing systems”. This consists of manufacturing processes that describe methods in the product realisation chain. Furthermore, terms such as “equipment” and “resources” describe the technologies used within a manufacturing process for product realisation. “Resources” may span from humans to machinery, regardless of automation status, whereas the equipment defines the supporting tools such as tooling and manual tools.

Because product features vary, the term “tooling” centres on two individual functionalities. The first describes the activities occurring between a manufacturing resource and a product, while the second focuses on fixing the product in a set of coordinates defining position and orientation, as dictated by the relevant manufacturing process. The latter functionality is also known as “workpiece-holding”, while the family of tooling providing the technological background is termed “fixtures”. The activity relating to this functionality is called “fixturing” [3].

Since fixtures and fixturing terminology are established within the family of production systems, the development of fixtures with varying features can be mapped chronologically to changes in production system paradigms. For this purpose, the adaptation process for each subfamily within a production system (in respect of the impact of paradigm shifts) can play an important role in facilitating the development approaches of fixtures. The adaptation process, in particular, forces particular subgroups to shape their functionalities to fulfil their new tasks according to the new requirements adopted by the emerging production system [4]. Since the adaptation process is completed with the emergence of new technologies, a feedback cycle is initiated to evaluate subgroups’ fitness in respect of the new paradigm, based on an input-output relationship determined by performance indicators [5].

Formulating the concept of flexibility in production systems allowed an example of chain reaction-like changes to be described for fixtures. Demand for product variety put pressure on production systems to be more responsive and so a new paradigm started to emerge, shifting the subgroups from mass production and towards flexibility, without compromising cost-effectiveness [6]. As the functionalities that were moving towards flexibility became dominant, new systematic working approaches were shaped and then assessed. Subsequently, this flexibility-infused production system philosophy became known as “Flexible Manufacturing Systems” (FMS) [7]. As with the other production system subgroups, fixtures were also set in motion for a shift. Within mass-production environments, fixtures were engineered and built around a single workpiece and its associated technical requirements (such as stiffness, accuracy and repeatability). This created the group of fixtures known as “dedicated fixtures”. With FMS, a concept was initiated in which standardised modular components were assembled to replace dedicated fixtures. By using Meccano connections and minimising the dedicated components at those points where the fixture interacted with the workpiece, a new fixturing approach called “modular fixtures” was generated. The use of modular fixtures became popular, particularly in the automotive and aerospace industries [8, 9]. As well as being triggered for a shift in the fixturing approach, modular fixtures were also evaluated (according to a new set of generalised parameters defined by the emerging paradigm) to determine their fitness for FMS [10]. As well as the dynamics occurring in physical form, the impact of shifting dynamics is also felt in design, deployment and operational aspects (in which methodical approaches are created, in a process spanning all phases of fixturing) [11, 12]. Consequently, the interaction between FMS and its subgroups established one of the first examples of how a paradigm shift takes place, along with its dynamic relationship with its subgroups.

Not limited to FMS, various paradigm shifts also influenced the emergence of new fixture types. Following the FMS steps, a new paradigm shift was initiated under the name “Reconfigurable Manufacturing Systems” (RMS) with an emphasis on optimising the flexibility of manufacturing technologies, using reconfigured automation technologies rather than general-purpose flexible solutions [13]. Triggered by optimised flexibility initiatives, fixture solutions started to adapt reconfigurable technologies into the fixture body. This allowed fixtures to surpass physical design perimeters and be reconfigured using motion technologies [9, 14-16]. Furthermore, new potentially feasible areas were also identified as new technologies started to be used in fixtures. With each paradigm introduced, increasing demand for product quality was met by the availability of motion technologies in fixtures, with several different workpiece-orientated solutions (such as force-controlled clamps [17]) formulated to meet performance demands. Later, the capacity of fixtures to regulate their elements to safeguard process requirements came to be known as “fixture activeness”, whereas the term “active fixtures” was coined for categorisation purposes [18]. As with FMS, RMS also engaged in the preceding hierarchical relationship with fixtures while establishing a set of general performance requirements and measuring how efficiently designed fixtures were able to meet them. Hence, a dynamical relationship around the concept of efficiency was established between each paradigm and its fixtures. Thus, the fixturing efficiency describes – and can be measured as – the state of a fixture’s fitness, according to a set of requirements prescribed by the production system at which the fixture is aimed. In addition to production system demands, the efficiency of a fixture can also be influenced by incorporating active features that interact with product and process-level requirements.

Contrary to the expectation that manufacturing industry would be able to deploy from various solutions as the efficiency had been defined, the fixtures used by manufacturing industry remained limited to the dedicated and modular types. This phenomenon can be explained from two particular perspectives. From a technological perspective, dedicated and modular fixtures are designed systematically in respect of a particular product and process. This, in turn, enables those fixtures to be optimised according to the quantifiable requirements of the product and process and, hence, increase their efficiency [19, 20]. From a managerial perspective, the efficiency of dedicated and modular fixtures was derived from cost-related metrics defined comprehensively for a mass production paradigm [21-23]. When proper metrics are adopted, the design process and use of dedicated and modular fixtures are further established around the notion of efficiency [24, 25]. This phenomenon is also consistent with the lessons learned from performance measurement systems (PMS), that the efficiency of each element in a production system needs to be measured by adapting overall metrics designed for the manufacturing paradigm in which the particular technology is operating [26].

Unlike the state of efficiency of dedicated and modular fixtures according to the mass production paradigm, the efficiency of flexible fixtures remained ambiguous. Statements consistent with the above conclusion have also been made in recent publications reviewing flexible fixturing technologies. These concluded that flexible fixtures cause cost and time inefficiencies, as their technological capabilities increase even though their capacity for flexibility in respect of a product and process was well justified [25, 27, 28]. Moreover, various flexible fixtures also result in trade-offs beyond flexibility and cost as a single technological choice brings about a chain of unique activities, resulting in different performance values for time and quality [14]. It therefore becomes apparent that flexible fixtures require a body of knowledge to be established which defines their efficiency beyond the parameters used for state-of-the-art. Furthermore, as with dedicated and modular fixtures, the definition of such efficiency needs to be used effectively so as to facilitate more efficient use of flexible fixtures. Consequently, this thesis identifies the previously mentioned phenomenon as the research gap in flexible fixtures and will bridge critical points so as to advance the efficient use of flexible fixtures.

1.2 AIM AND RESEARCH QUESTIONS

Based on the research gap identified in the previous section, the aim of this thesis is to increase the efficiency of flexible fixtures in the manufacturing industry. Consequently, the following research questions have been formulated to facilitate the aims of this thesis:

RQ 1) What are the criteria that can be used to describe the efficiency of flexible fixtures?

The first research question focuses on identifying a foundation upon which a description of efficiency can be based. The question aims to guide this thesis in analysing and generating criteria as input to the second research question:

RQ 2) How can these criteria be used methodically in the design of flexible fixtures?

The second research question guides this thesis in methodical use of input from the first research question. Furthermore, it aims to incorporate the stages of fixture design into the efficiency criteria. Moreover, the question aims to discover further potentially feasible areas in which this efficiency may be realised.

RQ 3) How can flexible fixtures be actively controlled to increase their efficiency?

The final research question aims to advance the answer provided in the second research question by focusing on the use of flexible fixtures from a control point of view.

1.3 DELIMITATIONS

The efficiency analysis presented in this thesis is delimited to cost, time, quality and flexibility perspectives. In other words, aspects of sustainability and ergonomics (such as ease-of-use) are excluded from this thesis, even though they are important drivers. Furthermore, this thesis will focus on reconfigurable fixtures. Fixtures of a modular and phase-changing nature will not be presented. However, relevant research will be covered in the frame of reference, along with relevant justifications.

Moreover, the term "control" describing the activeness of a fixture is delimited to the fixture device with linear control theory in mind, as it is reasonable to assume that a designed fixture operates with elements obeying the superposition principle. However, this thesis acknowledges that the workpiece, process and individual components of a fixture can lead to nonlinearities requiring nonlinear control approaches. Since these approaches require specific analyses of an individual workpiece and process, classification and generalisation are beyond the scope of this thesis.

Similarly, the workpiece analysis in respect of its mechanical properties for fixture design is excluded from this thesis as it represents a different body of research. Additionally, the industrial application of solutions developed within the body of this research are excluded from this thesis as an undertaking of that nature would require major time and financial resources that are beyond the scope of the available doctoral timespan.

1.4 THESIS LAYOUT

The first chapter laid out the background information, aim and research questions, Chapter II presents the frame of reference on fixture chronology, efficiency, design and control. Chapter III presents the research methodology deployed. Chapter IV gives a summary of the publications of this thesis. Chapter V provides answers to the research questions and an evaluation of the research approach, verification and validity. The conclusions of this thesis are drawn in Chapter VI.

II

FRAME OF REFERENCE

This chapter aims to present the fundamentals and state-of-the-art for fixtures. Fixture types will be presented first, followed by an investigation of the current state of flexible fixture efficiency. The third section will present the design of flexible fixtures, while the fourth will explore state-of-the-art for active fixture control. A summary closes the chapter.

2.1 DEDICATED & FLEXIBLE FIXTURES

To meet the demands of mass production in which a minimum number of product changeovers were required for high-volume production, fixtures were designed to secure the geometry of a specific workpiece. Based on this definition, a fixture was developed consisting of four components, namely: frame, body, locator and clamp. The frame of a fixture describes the component that establishes a base for the remaining components, whereas a fixture body is the intermediary component that facilitates locators and clamps relative to the frame. The locators and clamps are the components that locate and secure a workpiece respectively [3]. Using the above terminology, a dedicated fixture can be described with respect to the permanent connection used to secure individual fixture components fixture with respect to a specific workpiece. Thus, by permanently locating these fixture components at specific coordinates, a fixture becomes dedicated. This introduces the term “dedicated”. A dedicated welded fixture and its components are illustrated in Figure 1.

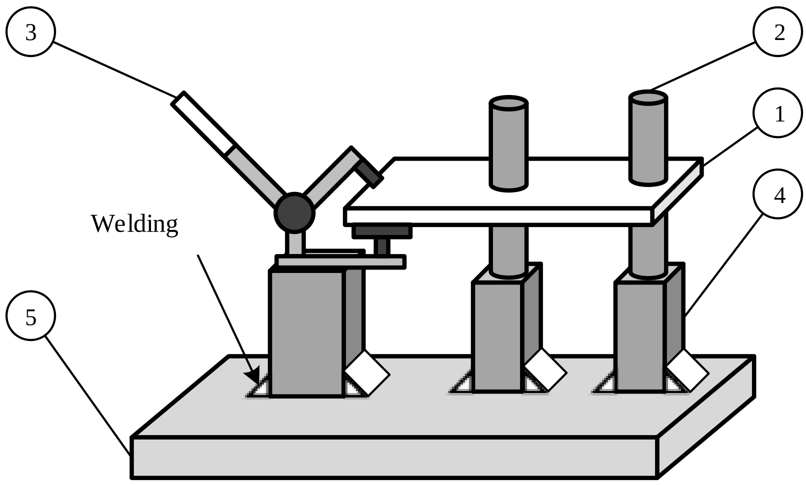


Figure 1. A dedicated welded fixture with: (1) workpiece, (2) locator or unit, (3) clamp, (4) fixture body and (5) frame.

As demand for product versatility increased, the need for flexibility in production systems translated into a variety of production technologies. Out of this demand, modular fixtures emerged [29] and the concepts of modularity and standardisation in designing modular fixtures became prominent [30]. In this design approach, standardisation was delivered via modular building blocks, in fixture components that did not interact with the workpiece. In addition, the connection type used to build the fixture blocks was a Meccano connection as, unlike welded connections, this feature allowed modular fixtures to be rebuilt [31]. Due to the vast geometries and design of modular fixtures, a classification scheme was proposed by Shirinzadeh [32] and Dai, et al. [33]. This covered element geometry and connection types such as T-slot and hole-matrix systems. In addition, Kihlman, et al. [15] proposed a box-joint system as a modular approach to fixtures, with beams connected by bolted plates. The modular fixtures in relation to dedicated fixtures are illustrated in Figure 2. With the introduction of modularity, manufacturing industries evaluated modularisation and applied different modular fixtures. In high-volume production systems, modular fixtures resulted in low performance due to the increased cost and time restrictions of modular fixtures along with design complexity. Meanwhile, manufacturing sectors, such as aerospace, combined modular and dedicated fixtures to compensate for the restrictions discussed above [25, 34].

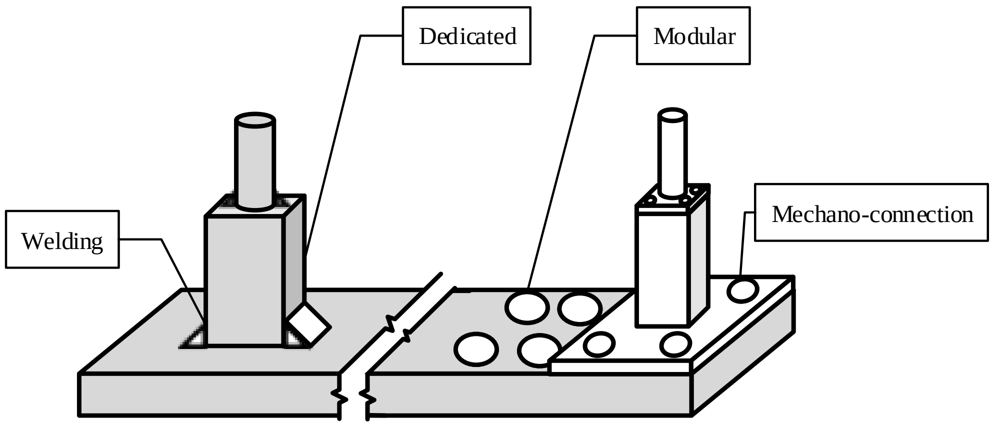


Figure 2. Modular fixtures in relation to dedicated fixtures.

Because the demand for flexibility was not directly met by modular fixtures, academia proposed different forms of flexible fixtures, such as those using phase-changing materials [35]. In these, a phase-changing liquid (such as electrorheological fluid) was placed in a container and a workpiece immersed in it. The fluid was then excited by electricity to change its phase to generate pressure in the container [36]. Magneto-rheological fluids were also investigated alongside electrorheological fluids by Rong, et al. [37], with a magnetic field used as an attractor. In both cases, the authors reported promising results due to the load-bearing capacity of phase-changing fixtures. However, Bakker, et al. [27] reported that the use of phase-changing materials was found to be toxic. This added restrictions and complexity in justifying the use of phase-changing fluids in fixtures.

As the aforementioned flexible fixtures yielded unsatisfactory results for meeting the cost and time demands of production systems, interest was drawn to a new type of flexible fixture manipulation. In this new form, various flexible fixtures were envisaged as being reconfigurable, with a fixture body (such as clamps and locators) adjusted to a new position without rebuilding. These came to be known as “reconfigurable fixtures”. For example, Asada and By [38], Asada and Fields [39] and Asada and By [40] designed flexible fixtures that were reconfigured to new positions on a magnetic chuck, using an externally articulated robot. The use of reconfigurable fixture bodies was also investigated in respect of process requirements, design principles and assembly sequencing [41, 42]. Moreover, the concept of reconfigurability in flexible fixtures was reconceptualised by using kinematic joints. Chan et al. [43] proposed using hydraulic and pneumatic actuators to reposition locators in a flexible fixture. Sela et al. [44] developed a combination of reconfigurable and modular components, in which locators and clamps were reconfigured in height and rebuilt laterally. Du and Lin [45] proposed "three-finger system", in which actuated revolving pins were reconfigured to locate and secure a workpiece. Sherwood and Abbott [46] developed the "POGO™" system, in which linear actuators coupled to vacuum grips (with passive spherical joints between them) were distributed over a fixture frame in a specific pattern, to adjust to various shapes and geometries. Walczyk and Longtin [47] proposed a reconfigurable pin with electromagnetic and pneumatic locking mechanisms. Al-Habaibeh, et al. [48] proposed a reconfigurable array of pins actuated by springs or pressurised medium to adapt to the geometry of a workpiece. In respect of pin reconfiguration, recent reviews [49, 50] suggest that these types of reconfigurable fixtures have increased design complexity and require expensive control systems that need to be addressed if they are to become competitive fixture solutions.

While these problems were being addressed, RMS introduced the use of kinematic structures as flexible fixtures [13]. Articulated kinematic structures with several kinematic joints attached serially were among the first examples of kinematics-based flexible fixtures. A six-degrees-of-freedom (6-DOF) gripper was proposed by Yeung and Mills [51], Yeung and Mills [52] for assembling sheet-metal parts in the automotive industry. For this, the authors conceptualised the use of a gripper attached to process robots.* Similarly, a closed-loop bar mechanism with suction cups as an end-effector was proposed as a fixture gripper for a process robot by Arzanpour et al. [53, 54]. As with closed-loop kinematics, parallel kinematics machines (PKM) with various structures were also proposed as flexible fixtures. A manual Stewart-Gough platform was proposed by Kihlman and Engström as affordable reconfigurable tooling (ART) [55, 56] in the assembly of aerospace components, with a process robot used to position the PKMs in coordination with a laser tracker. Three-limb PKMs were also used in similar assembly processes. Kihlman, et al. [15] proposed the use of "tripods" and "octopods" to demonstrate the range of process requirements that the PKMs could satisfy. Similarly, three and four DOF PKMs were also evaluated for automotive body-in-white (BiW) assemblies by Yu, et al. [57].

As flexible fixtures rely on various shapes and functionalities, several classification schemes were also proposed by academia. Grippo, et al. [58] and Shirinzadeh [32] classify fixtures in respect of "modular fixtures, automated clamps, phase-change and memory metals". Bi and Zhang [25] classify flexible fixtures, based on their number of components, as "single" and "modular" structures. For single structures, the publication classifies phase-change type flexible fixtures, whereas modular structures represent both modular and reconfigurable fixtures. Kihlman [59] reviews flexible fixtures in three categories as "modular, flexible and CNC-controlled". Bakker, et al. [27] classify flexible fixtures more extensively than the previous authors and suggest such categories as "automatically reconfigurable", "modular", "flexible pallet", "pin-type array", "sensor-based", "phase-change", "baseplate" and "custom". To facilitate the terminology of this thesis, a classification scheme will also be presented based on the common features of the flexible fixture applications given in earlier sections.

A flexible fixture may be initially categorised in respect of its physical form and features. In physical form, a flexible fixture can be rebuilt (such as modular fixtures), reconfigured (such as PKMs and articulated structures) or phase-changed (such fluid-bed systems) to provide flexibility. Thus, a rebuild-type flexible fixture needs to be rebuilt from its components at a

* It is important to note that the authors of [50] and [51] refer to the aforementioned gripper as a fixtureless assembly. However, by definition a fixture can be any device that locates and secures a workpiece during a process. Therefore, a gripper that performs locating and securing is recognised as a fixture in this thesis.

different location. A reconfigure-type flexible fixture, on the other hand, is adjusted using its internal kinematic components. Finally, a phase-change-type flexible fixture is immersive in that it requires a workpiece to be immersed in a fluid medium.

In respect of features, any physical form of a flexible fixture can be further classified according to its actuation, positioning/connection type and activeness. The term actuation describes the motion-generating element of a flexible fixture, be that internally by motors, or manually or externally as with a process robot. The positioning/connection type describes the flexible fixture's means of maintaining a predetermined location. This activity can be realised via a fluid medium, mechanical connection (such as bolting or shaft collars) or a magnetic power source (such as a motor).

The activeness term describes whether the flexible fixture can correspond to changes in process parameters (such as input measured via integrated sensors). Thus, internally supported activeness describes a flexible fixture with integrated sensors and independent of any external measurement tool. However, externally supported activeness requires an external measurement tool, such as a laser tracker. Adaptive material activeness describes the servo reaction of a medium under process variations, as in phase-change fixtures. Consequently, a flexible fixture's physical form and features can be combined and categorised regardless of its geometry or custom features. This classification scheme is illustrated in Figure 3.

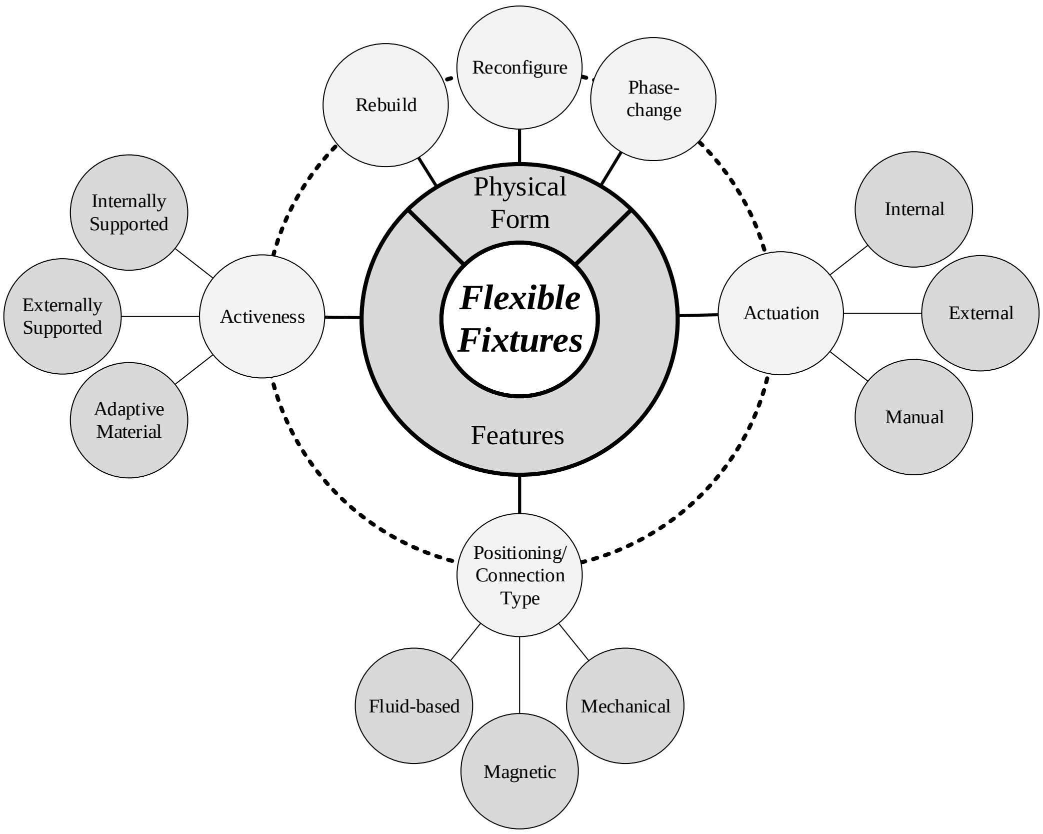


Figure 3. Flexible fixture classification proposed by this thesis.

2.2 FIXTURE EFFICIENCY

Regardless of whether they are dedicated, modular or reconfigurable, fixtures are designed and developed according to a set of criteria covering the features of workpiece, process and production system. This section will identify the criteria that establish the understanding of fixture efficiency, initially from a fixturing perspective. The efficiency of fixtures will subsequently be investigated from a production system perspective.

2.2.1 FIXTURING AND EFFICIENCY

In a typical fixture design (regardless of whether dedicated or modular), recent reviews by Boyle, et al. [60] and Kang, et al. [61] identified six fundamental parameters which fixtures must satisfy in order to locate and secure a workpiece. These parameters are used in fixture verification in relation to a product, process and target production system and are defined as: 1) stiffness-related requirements, 2) tolerance expectations, 3) operability demands, 4) necessity of accessibility, 5) cost and 6) time threshold. A similar categorisation of fixture verification parameters is also offered in [62, 63], where four criteria are considered (1) workpiece requirements (tolerances and geometry assurance), 2) norms of the target production system, 3) usability and 4) cost. Based on these criteria, several fixture evaluation techniques have been developed by academia.

Regarding stiffness-related requirements, a fixture’s efficiency is evaluated based on two fundamental notions: workpiece motion and fixture deformation. In analysing the stiffness of a workpiece during a machining process, a workpiece is discretised by finite element analysis (FEA) and forces occurring during the machining process are simulated [64]. By setting boundary conditions for the workpiece relating to clamps and fixture locators, deformation is analysed and the forces that fixture elements must exert are determined [65, 66]. The output of the workpiece deformation is termed the “stability” of the workpiece. This output can be either binary or a coefficient describing necessary adjustment [67]. Another approach to determining workpiece motion is based on determining the locator configuration where a workpiece's all DOF is analyzed by the rank of "position Jacobian" if they are constrained by locators; thus, the workpiece is assumed motionless under machining forces [40, 68]. However, the latter method does not involve any force and moment equilibrium. This makes it more computationally efficient during the automated generation of fixtures but less accurate, due to the absence of equilibrium analysis [69]. The second notion of stiffness-related requirements relates to fixture deformation. The forces and moments occurring at the boundary conditions of the workpiece are translated into fixture elements by defining a contact model [70]. The deformation analysis is mainly conducted according to locator arrangement, with locators positions reorganised to match the stiffness requirement for each locator, under the forces exerted at the boundary conditions of the workpiece [71, 72].

The tolerance expectations for fixtures aim to increase the accuracy and repeatability of the workpiece location, during and after loading. The main analysis approach to tolerance analysis focuses on minimising locator errors, where an error in a locator’s position is translated into a position/orientation error for each feature in a workpiece [73]. In this context, there are multiple methods for achieving an optimal solution. For example, Kang, et al. [74] set locator tolerances reversely, based on the workpiece feature error while considering all features simultaneously. Moreover, Yu Wang [75] correlates locator tolerance to the output of optimal fixture layout design defined by the workpiece feature error. Geometrical variation in the workpieces is also considered in his study. Bansal, et al. [76] propose offering various setups for a workpiece. By developing a matrix to represent errors in features based on perturbation of each setup, the setup with the smallest error is chosen.

The accessibility of a fixture describes its collision-free state in respect of itself, the tool path and workpiece features. Unlike other efficiency criteria, fixture accessibility is represented by a binary value, with the effects of accessibility requirement translated into a detailed design characteristic rather than a performance indicator [77]. Thus, automatic fixture design includes accessibility checks for verification purposes. Efforts directed at automatic accessibility verification are mainly accomplished using geometric reasoning algorithms, in which geometric boundaries of fixture, tool path swept-volume and workpiece objects are crosschecked with each other for interference [78, 79]. If any collision is detected, fixture elements or tool path are manually modified to new positions after the verification [80].

The operability, cost and time demands of a fixture have garnered less attention concerning fixture efficiency as they are considered meta-performance.* However, some researchers focused on integrating these requirements into fixture efficiency in automated fixture design. Specifically, the stated requirements are mainly discussed in regard to fixture element cost, as the fixture body is either deemed to be modular plates or custom-made [81, 82]. Similarly, operability (such as weight and ease-of-use) and time (to load and use during production) are also examined from a setup planning perspective where a benchmark is proposed to be determined by the target production system [69]. On the other hand, the meta-performance of fixtures can be determined by the shifts in production system paradigms and relevant performance measurement techniques. Thus, the next section will introduce the influence of production system paradigms on fixtures, taken from the perspective of efficiency and design characteristics. This will complete the picture of fixture efficiency given in this section.

2.2.2 INFLUENCE OF PRODUCTION SYSTEMS

Every step that the production systems took in order to adapt to the ever-changing demands of customers affected more than operational, control and execution aspects of production elements where these changes shaped production technologies. Mass production was the first philosophy to have major impact [1]. The fundamental notion of mass production was based on maximised production with maximised standardisation; this meant minimised variety in products and technologies [83]. As mass standardisation was realised, the cost of producing goods became the focus. This was then translated into cost-based performance measurement of technologies, including fixtures [84]. With the focus set on cost reduction of production, a concept named group technology (GT) was developed in the 1950s where product variety was analysed and reflected onto production so as to reduce the number of setups which added no value to the product. The core principle of this approach was to group fixtures together according to product batches of a single variant [21-23]. With GT's influence of cost-based efficiency analysis on fixtures, a new field of competition emerged lean, world-class manufacturing philosophies drove fixtures to be more efficient in terms of quality and time [85]. Given the driving force behind their evolution, fixture operations progressed and setup analyses were conducted to reduce the cost- and time-wise wastes, which enabled a continuous flow in production. This concept came to be known as "single minute exchange of dies" (SMED) [86].

With the dominance of mass production and its celebration of cost, quality and time efficiencies, demand for customisation began adding pressure to production systems [87]. Subjected to

* Meta-performance is a general term coined by this thesis. It relates to the classification of production system elements given in Chapter 1 and evaluation of a production system's performance.

customisation stimuli, production technologies began evolving around the notion of flexibility, so as to meet customisation demands. This emerging system of technologies formed “flexible manufacturing systems” (FMS) [88]. Following their emergence, a new parameter appeared: flexibility [89, 90]. Naturally, dedicated mass production fixtures performed poorly in respect of flexibility and, as discussed in Chapter 1, a new flexible fixture technology called “modular fixtures” was created [91].

With a rush on maximised flexibility, the progress of the remaining parameters was hindered – which led to the efforts of solving the conflict by means of optimising the four parameters [34]. The optimisation challenge over regarding the operational aspects of flexibility in production systems was tackled by a new philosophy termed “agility” where the production systems deployed by agility were named “agile manufacturing systems” (AMS) [92-94]. Since AMS brought no new technological solutions, the challenges of fixtures and production technologies remained unresolved until a new concept called “reconfigurability” was introduced by Kusiak and Lee [95] and Lee [96] in 1997. Interestingly and concurrently, Rogers and Bottaci [97] developed an analogous philosophy based on modularity called “modular production systems” (MPS). Following reconfigurability and modularity in production systems, Koren, et al. [13] introduced “reconfigurable manufacturing system” (RMS) as a production-system-level application of the preceding philosophies and offering complete technological descriptions. These technological descriptions were then grouped according to different characteristics by Mehrabi, et al. [98] and Koren [99] as follows. Customised flexibility (1) requires that each production technology offers the correct degree of flexibility. Convertibility (2) describes the capacity of a production system to change to a different product family quickly. Diagnosability (3) demands that time spent ramping up for a product changeover remains short. Modularity (4) describes the capacity to replace a production technology swiftly. Integrability (5) requires each production technology to be compatible with the remaining technologies. Scalability (6) requires production systems to add new technologies in respect of an increase in volume, or vice versa.

As the stated paradigms shifted to meet customer demands, novel technologies and characteristics were introduced into production technologies, including fixtures. Not limited to their physical forms, performance evaluation of these technologies also shifted. A paradigm focusing on the performance of production systems called “performance measurement systems” (PMS) reaching to meet the need for appropriate evaluation progressed from cost-based performance measurement to encompass time, quality and flexibility parameters [5, 100, 101]. Furthermore, Folan and Browne [102] and Waggoner, et al. [26] elaborated on the aforementioned parameters and adapted them individually to the different elements of a production system. This allowed accurate quantifiable metrics to capture performance.

As for flexible fixture efficiency (particularly cost and time performance of fixtures), the statement about adapting metrics and characteristics can play an important role as the current efficiency criteria for fixtures only represent the fundamentals of fixturing principles where the impact of paradigm shifts is not considered. Consequently, this section serves this thesis a capture of the efficiency understanding from both a fixturing perspective as in Section 2.2.1 and production systems perspective a summary illustration of which is shown in Figure 4.

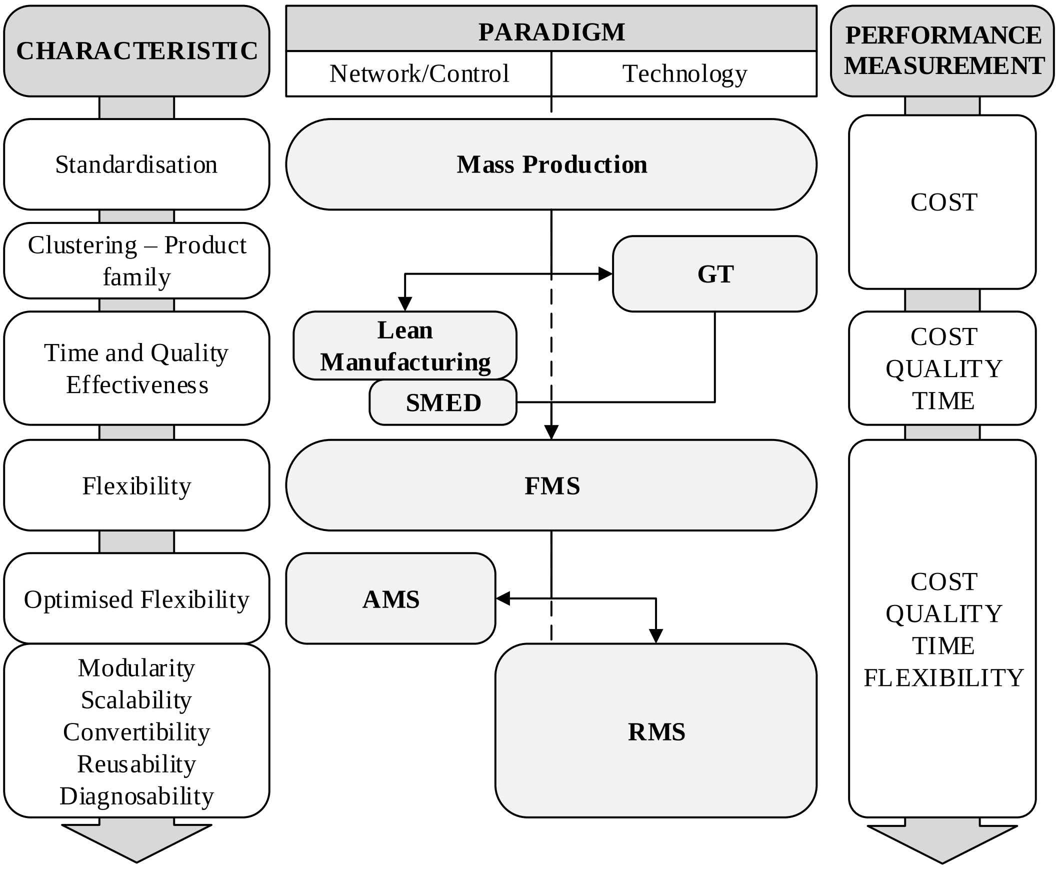


Figure 4. Production system paradigms and their characteristics and performance parameters.

2.3 FIXTURE DESIGN

This section presents a bridge between the fundamental fixture efficiency (discussed in Section 2.2.1) and the design of fixtures. The aim of this bridge is to show the efforts of academia and industry to use efficiency criteria in systematic design processes. To this end, the fundamentals of fixture design will be presented first, followed by a discussion of efforts to automate the design process.

A fixture design is realised in a procedure of five fundamental steps. The notion behind this procedure is to establish parts of the fixture, starting with the elements in contact with the workpiece and going on to fixture body design. Firstly, a fixture design is initiated relating to the geometry (such as dimensional features and physical requirements of the workpiece and efficiency criteria, as shown in Section 2.2.1). Secondly, the output of the initial criteria analysis is translated into setup planning. Thirdly, the setup information is complemented with locator and clamp elements (with information about their positions and types). Fourthly, fixture elements including the body are designed in detail. Finally, a verification analysis is conducted and any necessary modifications are made [103, 104]. These fixture design steps are illustrated in Figure 5.

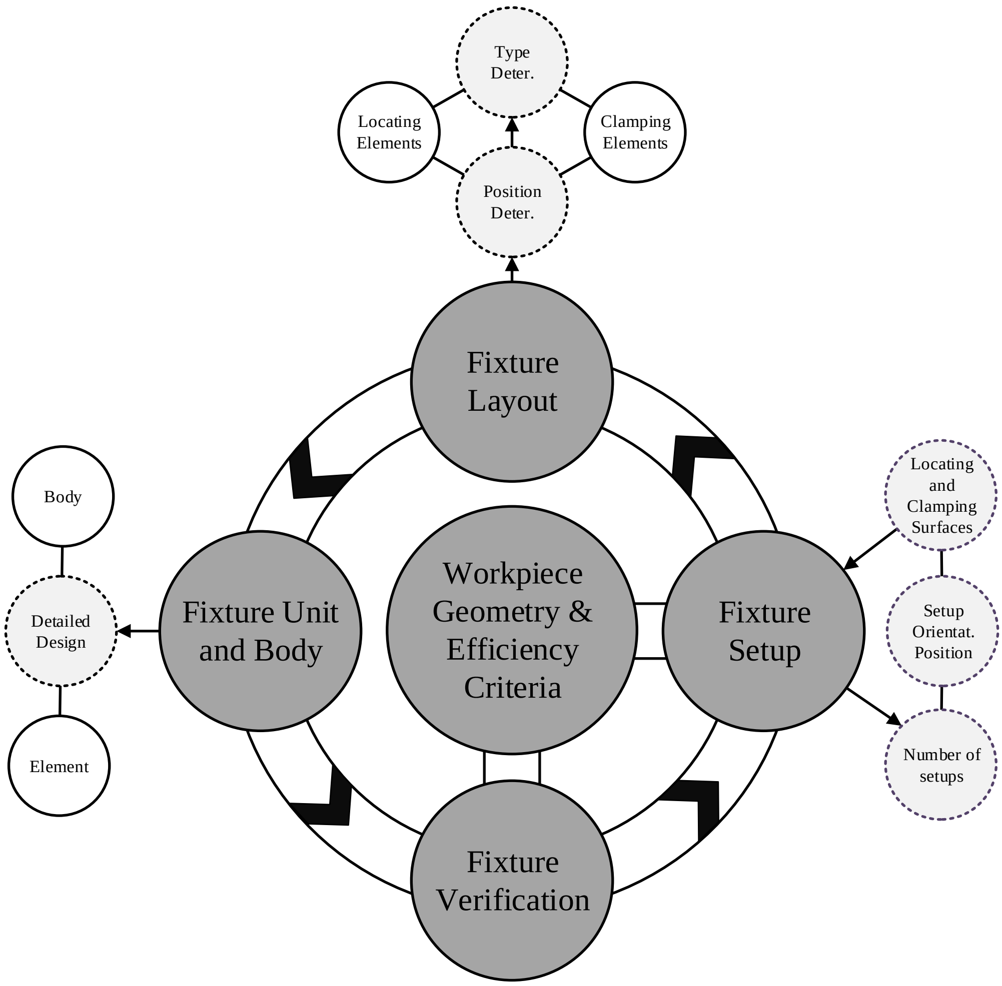


Figure 5. Fundamentals of fixture design process in five steps (adapted from Hargrove and Kusiak [104]).

With the overall design procedure specified, each step can now be examined in detail. In the setup planning step, the objective is to establish the position and orientation of the workpiece in regard to the process technology, be that machine or human. The positional data and geometric features of the workpiece are used to determine the surfaces with which the fixture's locators and clamps will interact [105]. The fundamental objective of the research in this step is to find the minimum number of setups required to complete the process, by gathering the surfaces and features to be machined into a group [106]. In so doing, academia offered different techniques for tackling this minimisation objective. One of them, graph theory, has been used to establish a precedence relationship, based on either machining order and geometrical features [107] or tolerance error mitigation [108]. Another approach to setup planning is to use the heuristic knowledge of the experienced fixture designer. Wu and Zhang [109] propose an "object-oriented" technique that adds knowledge and process information to the workpiece, allowing relevant features of the workpiece and its behaviour during machining to be captured for setup planning. Similarly, Gologlu [110] uses the object-oriented approach to set a precedence relationship for machining and fixturing requirements, coordinated with automatic workpiece feature-recognition.

As the layout determination (the second step) correlates directly to the first step, the datum and clamping locations are determined according to the setup information transferred from the first step [111]. As discussed, the objective of this stage is to ensure that the workpiece is properly located and a well-known method called “3-2-1” is often used [112]. For this step, Boyle, et al. [60] classify the research into layout planning according to whether optimisation is sought (where optimisation is conducted according to the fixture efficiency defined in Section 2.2.1). Case-based reasoning has been deployed by academia in cases where optimisation is not used. Kumar and Nee [113] developed a procedure that initially recognises the features in a workpiece and then automatically creates setups. By correlating these setups to previous cases, the fixture layout can be modified accordingly. Wang and Rong [114] use previous cases to generate conceptual welding fixtures by developing a three-level, case-based reasoning model. In addition to experience-based methods, neural network-based approaches are also considered suitable. Lin and Huang [115] use a neural network to recognise the features of a workpiece and generate a fixture cluster based on GT. Multi-objective optimisation, genetic algorithms and gradient approaches play an important role in layout planning optimisation techniques. Among the notable contributions, Pelinescu and Wang [116] offer a multi-objective optimisation study based on workpiece constraint and contact forces. Similarly, Wang, et al. [117] propose a multi-objective optimisation methodology, which optimises the fixture layout by considering locator accuracy, repeatability and forces occurring at the clamps. For layout planning using genetic algorithms, Wu and Chan [118] develop a procedure for optimising the layout according to workpiece deformation due to process forces. Another example of using genetic algorithms is a study offered by Kashyap and DeVries [64], in which the FEA of a workpiece in a prospective fixture layout is used to minimise deformation at locator points. For layout optimisation using gradient approaches, De Meter [119] offers a pseudo-gradient optimisation based on the contact nodes in the global stiffness matrix of the workpiece’s FEA model. Similarly, Li and Melkote [120] use a pseudo-gradient optimisation method at localised contact nodes of the workpiece to minimises deformation by using layout locators as variables. These two fixture design steps are usually referred as the analysis phase of fixturing. Minimal interference with the fixture body arises due to the choice of conceptual design approach.

Once the analysis of a fixture’s setup and layout has taken place, a conceptual design is translated into details for the fixture’s body, locators and clamps. The majority of the research has focused on detailed unit design. For detailed fixture unit designs, An, et al. [121] propose a system using a database of modular fixture components for standard fixture units and customised geometries to develop a fully configured fixture. In so doing, fixture body is represented by customised basic geometries that are adapted to the required dimensions when standard fixture units are assembled virtually on the workpiece. Hunter, et al. [122] propose a product development approach based on functions in which functional space is matched with commercially available modular fixture components. Cecil [123] also uses geometric reasoning to design clamps in detail, according to what clamping forces and locations have been determined. Other than dedicated and modular fixtures, a few publications consider the architectural design of remaining types of flexible fixtures where an architectural design refers to determination of initial functional requirements; and the relevant methodologies only consider the production system level requirements but not fixturing [124]. Consequently, the architectural approaches that focus only on a certain production paradigm with no correlation to the physicality of fixtures remain limited in terms of capturing the nature of flexible fixtures.

With the detailed design step reviewed, the cycle of fixture design becomes complete. A majority of the studies reviewed in this section are directly correlated to computer-aided fixture design (CAFD) and a historical outlook on the bulk of dedicated research can be traced in the reviews [11, 25, 32, 41, 58, 60, 104, 112, 125-130]. As pointed out earlier (and by virtue of the reviews that have been presented), the following concluding remarks regarding fixture design can be made. These are based on a shared feature observed in the reviewed research. The focus of fixture design relies mainly on the analysis phase in respect of fundamental fixturing parameters. Furthermore, the fixture design approaches that have been considered mainly use dedicated fixture bodies and modular elements to simplify the intensity of fixture design work. Unlike flexible fixtures, this consequence may be deemed natural, as designing dedicated modular fixtures requires intensive custom involvement from the fixture designer and relies heavily on their knowledge. It thus becomes apparent that a design procedure for flexible fixtures must be compatible with the analysis phase and verification step of fixture design and have appropriate efficiency criteria.

2.4 ACTIVE FIXTURE CONTROL

It is natural for every control scheme to be deemed active, inasmuch as the control system regulates a powered device. However, when it concerns fixtures, the term “active control” means more than a control system. Bakker, et al. [18] define active fixture control as the capacity of a fixture to modify its locating and clamping parameters to adapt to changes in the environment. An active fixture is considered inherently flexible as it has the capacity to modify its parameters with built-in flexible fixture elements, even if these are not designed for product variety. Hence, a review of the state-of-the-art will be given, based on efforts in controlling fixture elements and the designed purpose of the fixture.

The aim of controlling locator positions is to provide positional accuracy of a workpiece in a fixture, whether the process is machining or assembly. Chakraborty, et al. [131] present an workpiece accuracy-assured flexible fixture where an actuated base plate repositions an engine block with respect to the measurements made by a coordinate measurement machine. Yamaguchi, et al. [132] present a single DOF fixture locator complemented with a force sensor. When working with multiple synchronised locators, the developed fixture assembles a workpiece automatically by making adjustments based on force feedback. Olaiz, et al. [133] develop a flexible fixture that actively compensates for tolerances in a wind turbine component and assembles the components precisely. By using a linear actuator coupled to a feedback system, the flexible fixture adjusts the position of the workpiece to ensure that all workpieces are concentric. Culpepper, et al. [134] use a custom parallel kinematics machine whose actuation provided in ball-tipped shafts by motors capable of both linear and rotary motion for accurate positioning of a workpiece. In addition to machining fixtures, a flexible assembly fixture can also be used in an active control scheme. Jonsson [135] and [136] proposes using a coordinate-measurement assisted reconfigurable fixture where a non-real-time control scheme is utilised to accurately position the fixture before assembly.

Controlling locator forces aims to provide continuous contact and correct constraining forces between locator datums and fixture elements. This approach places particular emphasis on simultaneous control of position and force. Du, et al. [137] use three locators in a triangular pattern; one fixed, one rotationally actuated and one linearly actuated. By measuring the locating forces, a clamping-alike strategy based on direct position and force feedback is used to achieve optimal locator forces in respect of the workpiece’s stiffness. McKeown and Webb [138] report on the development of POGO-type linear actuators with suction cups at their end-effectors. These regulate locator forces whilst a stir-welding process is underway. Regarding actuator mechanics, a direct force feedback mechanism is used as a control strategy in the locators.

As with active locator control, clamping control is extensively investigated by academia and industry. The fundamental notion behind the active control of fixture clamps is to control the forces acting on the workpiece and regulate deformation to within acceptable limits, during such processes as machining and grinding [139]. Mannan and Sollie [140] propose a linearly actuated clamp to control forces occurring in direct feedback via force sensors. Based on the clamp developed by Mannan and Sollie [140], Nee, et al. [141] and Nee, et al. [62] integrate an active fixturing system by using a control strategy based on converting the force error to a position using a stiffness scalar. Ryll, et al. [142] develop an active fixture scheme with force-controlled clamps, to allocate the clamps to the correct locations initially. Papastathis, et al. [17] and Bakker, et al. [143] then suggest a design methodology based on the workpiece model and active fixture clamp, using both electro-mechanical and hydraulic actuation to generate forces. A general control strategy in the prescribed methodology is investigated and a direct force feedback scheme is recommended. Papastathis, et al. [144] present a custom reconfigurable fixture for aero-engine assembly and disassembly. This seeks direct force feedback on the clamps to regulate correct clamping forces. Zhang, et al. [145] describe a reconfigurable fixture solution for sheet metal manufacturing and assembly respectively and suggest a pneumatically controlled clamp. They develop an adaptive control system to compensate for force errors by using a model-based optimisation scheme.

The final aspect of active fixture control is workpiece chatter suppression during machining processes. Alongside passive elements such as viscoelastic dampers, this active chatter suppression describes the use of active fixture elements by generating an extra stimulus on the workpiece to suspend the chatter effect [146]. Rashid and Nicolescu [147] propose an active workholding pallet using several piezo actuators and force sensors. They develop an inverse model control using an inverse least mean squares filter to regulate the forces on the workpiece generated by the piezo actuators. Similarly, a development process for an active chatter suppression fixture is presented by Abele, et al. [148]. In addition, Brecher, et al. [149] present a similar piezo-driven workholding chuck using accelerometer and displacement feedback, to cancel the relative distance between the tool and workpiece. Sallese, et al. [150] propose a custom control strategy based on generating a low-frequency amplitude-modulated force, the signal content of which is determined by the external stimuli.

Certain similarities can be observed in these efforts to control fixture elements actively. They fall into three distinct categories: controlled component, control strategy and application. On the component level, the majority of the research focuses on the automation of locators and clamps individually in which fixture element dynamics can be drastically simplified. Moreover, the innate nature of flexible technologies (such as actuators) is reduced to a certain class of actions related to active control. On the control strategies level, the control objectives centre on the position and force control of locators and clamps. The majority of the research that has been conducted suggests the use of feedback control strategies such as proportional-integral-derivative controllers. In more expansive studies, the control schemes rely on process knowledge and specific actuator behaviour, such as piezo actuators stimulated by oscillatory disturbances. On the application level, the majority of active fixture research is dedicated to machining applications in which the concept of flexibility in fixtures is dealt with using modular components. The application of this knowledge beyond the confined nature of machining applications requires further investigation. In addition to direct similarities, a suggestion made by Bakker, et al. [18] and Gameros, et al. [28] relates to the importance of integrating the active control of fixtures into a design process with general fixture components. Such integration provides the necessary background for robust application of active control knowledge – which ultimately contributes to a fixture's efficiency.

2.5 SUMMARY & RESEARCH GAP ASSESSMENT

As Section 2.1 reveals, the solutions emerged to answer the need for flexibility in fixtures constitute technologies that have a nature of rebuilding, phase-changing and reconfiguration. Using the stated classification, the concept of flexibility in fixtures is afforded a physical representation that supports the necessary background to the delimitations in Section 1.3. Considering the hazard statements on phase-changing flexible fixtures and successful applications of modular fixtures in academia and industry, the relevant research gap for flexible fixtures from a physical form perspective can be determined for flexible fixtures with reconfiguration nature – which is also known as reconfigurable fixtures. Hence, the physical body that will constitute the technological representation of this thesis will manifest in the form of reconfigurable fixtures.

Having determined the technological representation of flexible fixtures, it becomes possible to propose a gap assessment for *RQ* 1. In the state-of-the-art analysis of fixture efficiency, two distinct points have been highlighted by this thesis. Firstly, the state-of-the-art recognises technological capacity as the fundamental efficiency factor as the majority of research focuses on creating versatile fixture solutions and applying efficiency evaluations based on technical capabilities. This statement can be observed in the lower degree of interest dedicated to the efficiency criteria for fixtures' cost and time efficiency criteria. This thesis has also shown that the same versatility in fixtures is triggered by shifts in production paradigms, particularly with respect to their expectations in relevant production technologies' characteristics. Conversely, these shifts and their performance expectations are not adequately translated into fixture efficiency, even though their characteristics have emerged in the form of various flexible fixtures. This can be seen clearly in the research into fixture efficiency, in which the fundamental criteria are mainly concerned with dedicated or modular fixtures. It therefore becomes clear that six fundamental parameters are not sufficient to evaluate the efficiency of a flexible fixture developed for a more advanced production system paradigm than mass production. Consequently, the research gap for *RQ* 1 can be stated as follows. Although there exists a technological versatility for flexible fixtures with respect to characteristics of newer production paradigms, the developed flexible fixtures lack the relevant efficiency criteria that are uniquely developed with flexibility in mind. Thus, new efficiency criteria should be proposed considering the production system level performance without neglecting a possible connection to the fundamental fixture efficiency criteria.

With *RQ* 1's research gap and direction established, a similar statement will be proposed for the design of flexible fixtures. Based on the design steps in Section 2.3, designing fixtures is treated as an inseparable process in which the input depends on the previous step's output. This implies that the design process is only suitable for dedicated fixtures in which all relevant aspects of that fixture have been developed according to the features of the workpiece and process. A similar conclusion regarding the state-of-the-art in fixture design can be reached from the exemplary work presented in each publication. The majority of design process applications use elements of dedicated and modular fixtures in which more advanced solutions have not been considered. Moreover, the lesser attention devoted to fixture body design results from dedicated-fixture-oriented thinking; this makes obstacles caused by workpiece-specific design hard to capture in a design process. Conversely, the fundamental notion behind flexibility is the decoupling of a fixture body from the design process, with the fixture body treated independently of the remaining steps. That said, the efforts towards maximised flexibility with FMS have led to the notion of optimisation – which also serves as a constraint in defining the research gap. Based on the state of the fixture design process and its predicament with respect to flexible fixtures, the research gap and direction statement for *RQ* 2 can be formulated as follows. The state-of-the-art design process for a fixture body is limited and only considers dedicated and modular fixtures. Furthermore, creating a design procedure for flexible fixtures based only on the notion of flexibility is not sufficient. Therefore, the efficiency criteria describing flexible fixtures must be included in the design procedure. Moreover, the body design procedure that is developed must remain consistent with the remaining fixture design steps, as it still has to function with other fixture elements.

The final aspect of this chapter focuses on active fixture control, with state-of-the-art considered under *RQ* 3. Section 2.4 explores state-of-the-art and shows that active control of fixtures has inherently flexible (specifically reconfigurable) tools; their parameters can be modified to ensure quality in a process. In the reviewed work, active fixture control is classified in respect of its objectives as force, position and chatter suppression control. Moreover, the control theory is somewhat diminished and only considers basic fixture elements. Even though the fundamental knowledge can still establish a background, it is still not sufficient to describe the additional dynamics introduced with advanced solutions such as PKM. Regarding control strategies, the majority of the dedicated research relies on typical feedback control schemes, with advanced control theory only used in the presence of special technologies such as piezo actuators. Moreover, these strategies are mainly oriented towards machining applications. The earlier findings of this thesis show the majority of academic work in this field has similarities to the state-of-the-art fixture design processes, in that they are tailored to a specific workpiece and process. Hence, in keeping with the suggested reviews, an apparent research gap and direction for *RQ* 3 is formulated as follows. The existing body of knowledge on active control is customised based on the workpiece, application and available technology. Thus, a generalised body of knowledge must be sought. The body of knowledge that is generated must set flexible fixtures as its target technology. The generalised control strategy must also remain either fully or partially applicable to a wide range of processes, regardless of workpiece geometry. Finally, the control strategy must integrate with the design process suggested by *RQ* 2 and enable efficiency evaluation for completeness purposes.

Although research gaps and directions differ from the state-of-the-art in fixtures concerning efficiency, design and control, it is important to acknowledge the success of dedicated and modular fixtures in industry. It is clear, from the attention given by academia, that past research does not question the capacity of these fixtures; fixtures rigorously developed and evaluated with the needs of a specific workpiece, process and production system in mind. The underlying mechanics of the above success relates to certain perspectives, namely: (I) technological capacity and diversity, (II) methodical design process for delivering a solution and (III) incorporation of appropriate characteristic and efficiency criteria. As the pragmatic fusion of these mechanics produces success in applications, a similar roadmap can be set for flexible fixtures. Hence, the *RQ*s and their identified research gaps also aim to fulfil the three perspectives on fixtures. This thesis will therefore use these perspectives to navigate the advancement of this research (particularly from a research approach point of view) and occupy the gaps identified in the *RQ*s.

III

RESEARCH APPROACH

Methodical development is an important pillar of scientific advancement. This chapter presents the research approach deployed in this thesis. Firstly, the terminology is established. Subsequently, the author’s theoretical perspective is presented. Finally, applied research methodology and methods are described, along with other methodologies.

3.1 TERMINOLOGY

From a theoretical perspective, the association of research to knowledge is essential in facilitating understanding. Thus, various association lexicons have been created. Guide-or-outcome-based approaches have been proposed by Bryman and Bell [151] where in a guide-approach hypothesis deduced by a researcher is investigated using empirical analysis. This method is also acknowledged as a deductive outlook. By way of contrast, a generalisation is made about the data collected via findings and observations, with the aim of creating a theory. This method is acknowledged as an inductive outlook. Unlike Bryman and Bell [151], Creswell [152] uses a lexicon categorisation based on data collection methods. In the proposed categorisation, numerical data collection methods classify a research approach as quantitative, whereas inductive-reasoning-based approaches are articulated as qualitative. Bryman and Bell [151] dispute the quantitative vs qualitative categorisation, based on the statement that deductive and inductive approaches can use both quantitative and qualitative data methods interchangeably. Thus, a categorisation based on “deductive” and “inductive” facilitates a more profound understanding. Given these findings, this thesis uses “deductive” and “inductive” as research approach terms, whereas quantitative and qualitative methods are treated as data collection activities.

In addition to research approaches, further terminology is also established to distinguish between research methodology and methods. According to Kothari [153] and Maxwell [154], the definition of good research includes a systematic approach to research design, with an order of definitions as important enablers in terms of appropriate support. In the order given by Crotty [155], research methodology is defined as the process of properly defined interconnected activities, with data collection activities identified as methods. This thesis uses research methodology as the process and research methods as data collection activities.

3.2 THEORETICAL PERSPECTIVE

Crotty [155] treats ontology as two distinct ends of a scale. At one end, there is a materialistic (or realistic) view whilst, at the other, there is idealism. Knowles [156] defines materialism as materials existing due to their interactions with each other, regardless of the interpretations of consciousness. However, idealism suggests that materials are the output of interpretations by consciousness. The epistemological standpoint reflects on the ontological scale and claims that knowledge is independent of one’s perception. Thus, objects and their meaningful truth can exist regardless of whether they are perceived. This is called objectivism, whereas the interpretative reflection on ontology is constructionism [155]. The framework comprising a body of beliefs, approach or stances is mainly coined as “theoretical perspective”, “paradigm” or “philosophical worldview” [157].

According to Creswell [152], theoretical correspondence with the objectivity-orientated ontological and epistemological statement is mainly framed in a post-positivist worldview, whereas an interpretative perspective is often framed as constructivist. Moreover, Creswell [152] classifies the characteristics of these theoretical perspectives in terms of determination or understanding, theory use or generation and data gathering. Subsequently, Creswell [152] sets out a table of conflicting characteristics to demonstrate how different worldviews impact the research methodology of a given scientific work.

Although these different worldviews differ drastically from each other and have gained an audience based on the notion that they cannot be easily deployed synchronously, contradicting ideas have also surfaced [157]. One such example is Tashakkori and Teddlie [158] , who propose that philosophical worldviews can be determined in respect of a research question. This makes it possible to combine different theoretical perspectives and methods to answer a research question. They argue that research questions may cover multiple facets of a philosophical worldview. This allows the different tools of each worldview to be combined in order to realise an answer for a particular question. This proposal was subsequently called a “pragmatic view” and paved the way for mixed methodology [157].

This thesis is governed by the principles of pragmatic view, which approaches with affinity to the research framework adaptation in order to facilitate a similar fusion environment. Particular emphasis is therefore placed on increasing flexible fixture efficiency and its three distinct perspectives as presented in Chapter II for determining an appropriate research framework. The first perspective is about establishing a technological solution to meet the technical demands and physical limitations of the product, process and production system. The second perspective is about establishing a methodical development process similar to the modular fixtures. The third perspective involved integrating production system characteristics and performance expectations into the design process. It is important to clarify the pragmatic worldview of this thesis in this particular description of efficiency. The use of technological solutions inherently requires a deduction-based approach with the basis of experimentation whereas design process and performance identification relate primarily to production system research; a juxtaposition of various quantitative and qualitative methods [159, 160]. Accordingly, it is important for this thesis to take a pragmatic worldview to realise answers to its research questions, which cover multiple facets of scientific rigour.

3.3 RESEARCH FRAMEWORKS

This section aims to present the available research frameworks developed for different disciplines and determine their suitability in respect of the theoretical worldview and nature of this research. Firstly, the section will focus on computer science and related frameworks. Secondly, frameworks developed for product development will be presented. Finally, research frameworks that have design science in mind will be visited.

Various disciplines, particularly the applied sciences, emphasise the importance of bringing industry and science closer by means of appropriate research approaches in which systems-level thinking plays an important role [151]. For example, in the computer sciences, research frameworks aiming to systematise the development of software systems have been proposed; the aim being to deliver scientific rigour and verifiable outcomes. Nunamaker Jr, et al. [161] proposed a systems development framework (SDF) to establish a set of activities for information technologies. This framework is initiated in a theory-building activity, in which the researcher aims to transform the studied phenomenon into a set of deterministic explanatory remarks. As the body of knowledge is established via theory-building, a prototype-like artefact is suggested, based on the remarks made. An experimentation process is then proposed, to investigate the comprehensiveness of established knowledge on the observed phenomenon and propose relevant modifications if needed. In the final stage, verified information is translated into a system representation via accurate conclusions. The SDF process is illustrated in Figure 6.

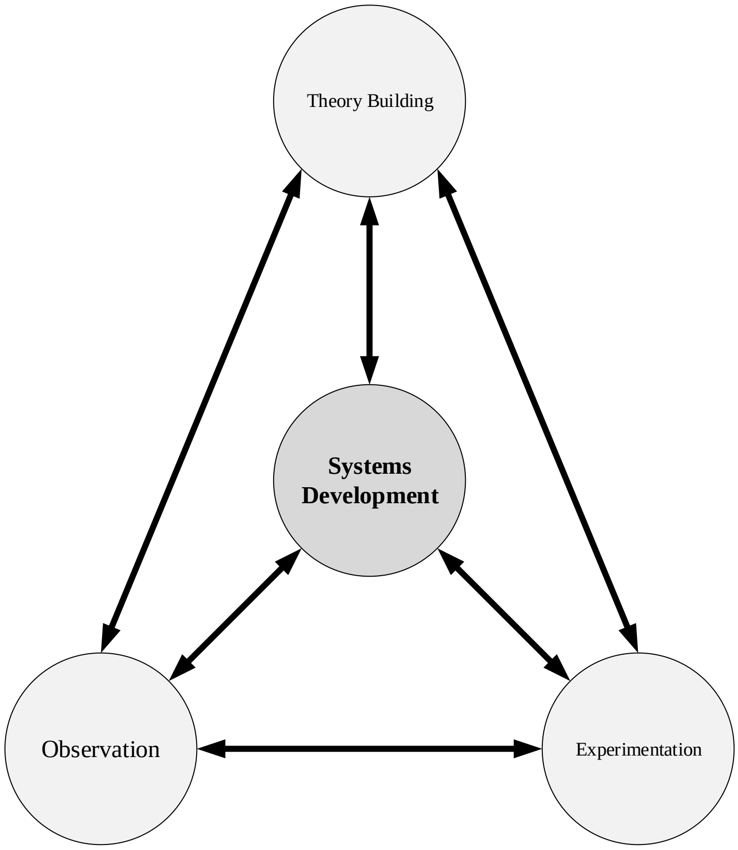


Figure 6. Systems Development Framework (redrawn from Nunamaker Jr, et al. [161]).

Similar to SDF, Industry-as-laboratory suggested by Potts [162] is an alternative framework that emphasises collaboration with industry by repetitively building a research agenda on an existing industrial problem. In this framework, an existing problem is transformed into a testable construct using research and development to be experimented upon in a different industrial setting. The outcome of these experiments is then iterated for the next version of the testable construct. The framework thus ensures a consecutive development environment for the research while maintaining a close connection with industry. A similar research framework emphasising the importance of industry is the *Wingquist Research and Implementation Model* [163]. In this framework, a research problem and an industrial opportunity are jointly translated into a common research challenge. A demonstrator or prototype-based solution is then proposed; this transforms the research challenge into a product for industry.

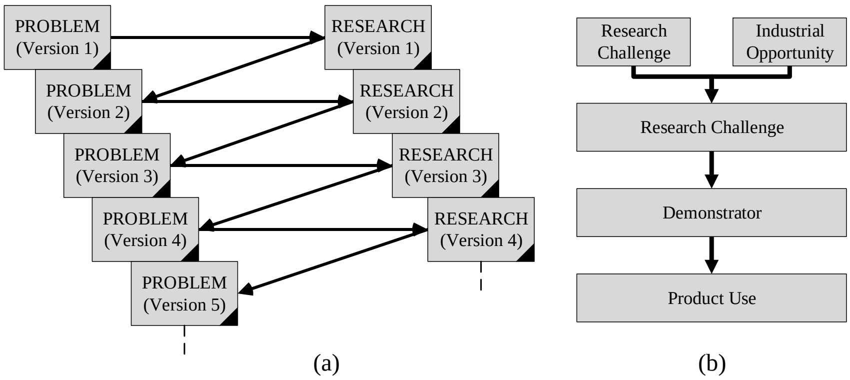


Figure 7. (a) Industry-as-laboratory approach redrawn from Potts [162] (b) Wingquist Research and Implementation Model redrawn from [163].

Instead of focusing on industrial collaboration, Eckert, et al. [164] suggest a research framework which designs a spiral of applied research (the Eightfold Path model of design research), as illustrated in Figure 8. This framework is initially divided into four main stages, with a feedback mechanism between each stage. In the first stage, an empirical study is tasked with identifying the mechanics of a design process. The mechanics it identifies are propagated into an evaluation phase by devising an empirical study. This study then seeks to validate and confirm the devised behaviour. In the second stage, a theoretical development process is initiated in order to convert the mechanics and devised behaviour into repeatable theoretical artefacts, such as design processes or mathematical models. For validation purposes, another evaluation stage is conducted, to compare the developed theoretical model with the observed data. Once validation is achieved, necessary tools and procedures are realised as support mechanisms in applying the theoretical model. Like previous stages, these support mechanisms are also evaluated in terms of user feedback in an experimental environment. Finally, the spiral is completed by testing the developed tools in a comprehensive industrial setup. Accordingly, the tools are then either revised or disseminated.

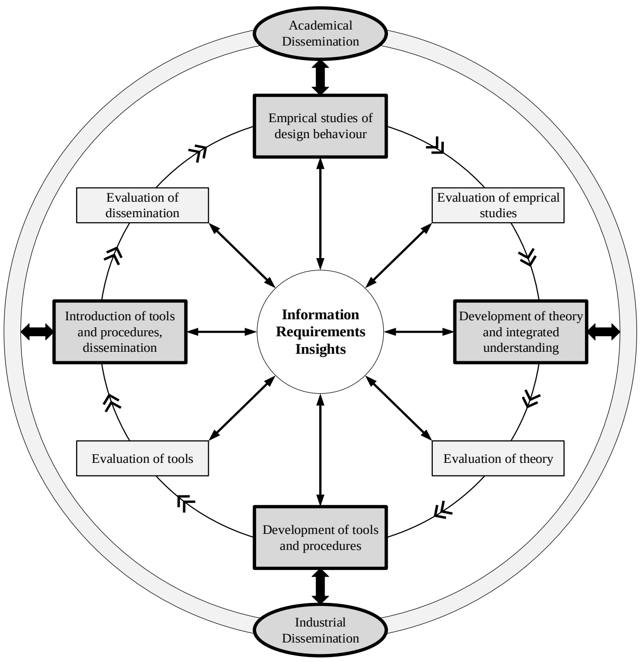


Figure 8. The spiral of applied research (redrawn from Eckert, et al. [164]).

Differently than the spiral of applied research, design research methodology (DRM) provides rigorous focus on the design research itself and extends the spiral of applied research by meticulously describing required activities and data collection methods [157]. As with the spiral of applied research, DRM consists of four consecutive stages. In the first stage, Research Clarification, literature reviews are suggested to clarify the research using research aim, questions and hypothesis to determine the goals of the design research. In the second stage – Descriptive Study I, an attempt is made to understand the studied phenomenon by realising a model describing the behaviour of the real-world problem. This model is complemented with success criteria, based on the empirical studies conducted. In the third stage, Prescriptive Study, the model designed in the previous stage is advanced by using prescriptive tools and methods to illuminate and elaborate upon the studied phenomenon, with the aim of achieving the research goal. Thus, a support structure is sought by using an impact model. The final stage, Descriptive Study II, proposes in-depth industrial testing of the prescriptive model to evaluate its effectiveness. The process of DRM is illustrated in figure 9.

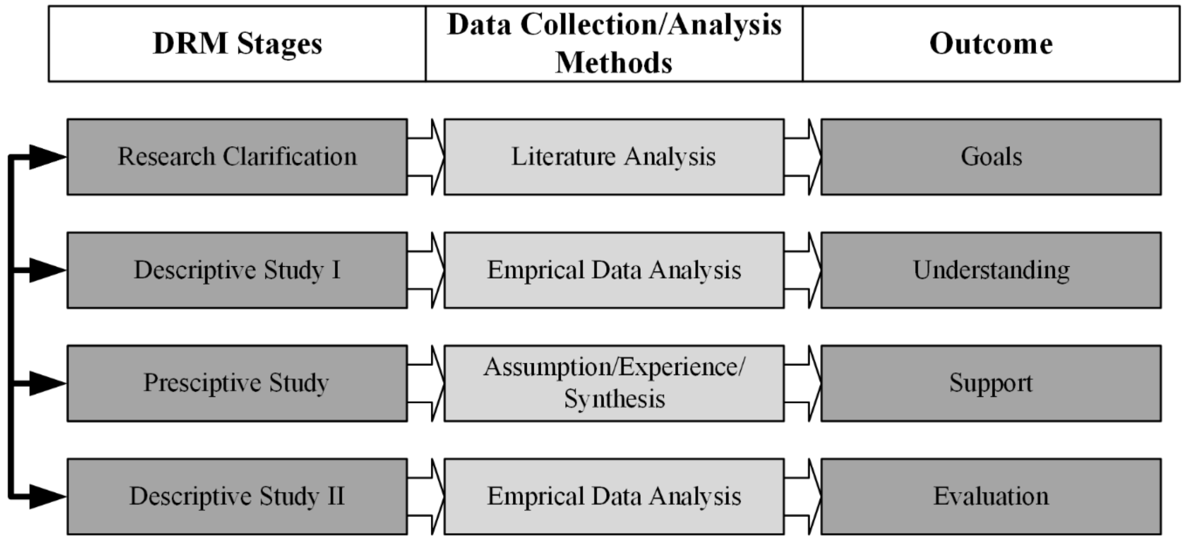


Figure 9. DRM – Design Research Methodology. Stages, Methods and Outcome (redrawn from Blessing, et al. [157]).

In addition to detailed stages, DRM also classifies possible data collection methods that can be conducted in each stage. In Research Clarification, DRM suggests review-based studies based on the available literature. For the remaining DRM stages, a combination of quantitative and qualitative empirical studies is suggested. These empirical methods include experiments, surveys and questionnaires for the quantitative studies and observations, interviews and case studies are for the qualitative ones. Moreover, DRM further specifies the types and purposes for which these empirical methods can be used. This classification proposes review-based studies to correctly position and direct the research by identifying the research gap, problem and relevant hypotheses. The comprehensive studies include a combination of empirical methods and literature studies to develop a body of knowledge. Initial studies present and formulate the results of this body of knowledge (developed in an earlier project) so that the results are utilised in other projects. The types and combination of studies appear in Table 1.

	Research Clarification	Descriptive Study I	Prescriptive Study	Descriptive Study II
1	Review-based	Comprehensive		
2	Review-based	Comprehensive	Initial	
3	Review-based	Review-based	Comprehensive	Initial
4	Review-based	Review-based	Review, Initial, Comprehensive	Comprehensive
5	Review-based	Comprehensive	Comprehensive	Initial
6	Review-based	Review-based	Comprehensive	Comprehensive
7	Review-based	Comprehensive	Comprehensive	Comprehensive

Table 1. Type of studies for DRM as remade from Blessing, et al. [157].

3.4 APPLIED FRAMEWORK

Among the presented frameworks in previous section, a commonality can easily be observed that iterative theory-building is emphasized. This commonality is also pertinent to the research questions of this thesis, which anticipate iterative knowledge transfer since the answer to each research question is used as a building block for the next. This may be described as vertical knowledge integration. Moreover, it is clear that each research question in this thesis interacts with different perspectives, as stated in Chapter II, which anticipates a horizontal integration of building blocks by synthesising the knowledge from these perspectives. Consequently, this thesis's aim demands a research framework that can support the expansion of research activities in a multidimensional setting, with parallel integration of the horizontal results to form a vertical system of knowledge blocks.

As the relationship between horizontal and vertical building blocks is established, further analysis of the state of the individual blocks must be instigated. For *RQ* 1, defining efficiency involves identifying technological capabilities, performance and characteristics that require individual analyses in different disciplines. Like *RQ* 1, the methodical design process of *RQ* 2 aims to synthesise interaction of the identified definition of efficiency, by deepening the analyses of their respective disciplines. Based on the outcome of *RQ* 1 and *RQ* 2, active control in *RQ* 3 expands the scope of efficiency and design process and establishes a link between control systems and the hitherto developed body of knowledge. The natural conclusion is therefore that each building block represented by publications requires a framework that supports multi-disciplinary knowledge development. Moreover, it is apparent that the synthesis of research questions in the horizontal and vertical dimensions needs a candidate framework directed at realising the aims of this thesis. In other words, both individual building blocks and their synthesis entail use of a framework specifying their details and features.

Based on that reasoning, available frameworks can be tested for suitability to the nature of the research in this thesis. As a relatively abstract-level approach, Industry-as-laboratory suggests the iteration of results until a specific aim is fulfilled. Due to multidimensional knowledge requirements described, this framework may be deemed insufficient for the activities warranted by this research. Similar to Industry-as-laboratory, SDF offers no support for the integration of knowledge and, hence, this framework remains unsuitable. However, it is important to note that SDF provides a detailed approach to development that can offer structured support for individual knowledge blocks in this research. This is because the framework defines “system” as an individual product for which detailed definitions are made. Interestingly, Wingquist’s research model uses a similar framework approach to that of SDF, with a reduced level of detail. DRM, on the other hand, offers complete structured guidance. It has particular focus on knowledge integration by using smaller blocks and placing specific emphasis on the overall model. This enables DRM to be a suitable framework for research requiring wider scope and longer duration. On the other hand, DRM’s specific block definitions only emphasise a particular branch of product development that contradicts the nature of this research, which also seeks physical development. However, this conundrum can be mitigated by using SDF’s narrower approach.

Considering the multidimensional nature of this thesis and the capabilities of the identified research frameworks, DRM is an ideal candidate for a main framework in realising the aim of this thesis. SDF can also be used for individual blocks, as the scope and duration of their studies are shorter. However, it is natural for each framework to need a degree of adaptation to the nature of this thesis, as they are designed and developed for disciplines other than those being researched here. The next subsection will therefore identify these routes, challenges and conflicts and propose a path for using the candidate frameworks.

3.4.1 FRAMEWORK UTILISATION

As the frameworks offer a general perspective, it is important to transfer and adapt their support structure to the uniqueness of each piece of research [155]. In this section, the adaptation process will be presented top-down, starting with the DRM for the research questions and aim of this thesis. Moreover, the knowledge blocks (represented by publications) will be integrated into the specifics of the DRM. Finally, to complete the framework utilisation of this thesis, the intended use of SDF in individual publications will be given.

The first stage of DRM – Research Clarification – focuses on the elaboration of the research topic to generate an initial reference model based on evidence collected via literature review. This initial model aims to identify relevant criteria that correlate the results of the research with the aim of this thesis. When this statement is interpreted according to the nature of this research where efficiency in flexible fixtures is sought, a conclusion may be drawn; an initial understanding of the fixturing efficiency. This represents a partial answer to *RQ* 1. However, as Chapter II revealed, the current body of knowledge has not yielded clear results that can be directly correlated to all aspects of flexible fixtures. Therefore, it is important to conduct relevant studies to test and realise a precise reference model for this stage. This means that comprehensive studies involving development of existing flexible fixturing technologies must be included, in order to advance the current body of knowledge. Therefore, the conclusion regarding incorporating research clarification of DRM into the research of this thesis can be drawn, as per the following statements. The description of fixture efficiency and its relevant criteria may be partially identified for use in an initial reference model via a literature review, as stated in Chapter II and the cooperative knowledge integration of several studies. These studies are represented by Publications A and B. As with *RQ* 1, *RQ* 2 takes part in the clarification stage (as shown in Chapter II) that the body of knowledge for a design process is limited to dedicated and modular fixtures. Therefore, the study in Publication B will also seek to clarify and test the effectiveness of the design information given in Chapter II. Consequently, the outcome of this publication (for this stage) in respect of *RQ* 2 is the partial identification of important design steps in flexible fixture design and their comparison to the body of knowledge.

The second stage of DRM – Descriptive Study I – aims to elaborate on the initial reference model specified in the Research Clarification stage. In this stage, DRM uses the initial reference and conducts empirical studies to complement and advance the existing body of knowledge and thus develop a complete reference model representing the understanding of the research problem. Moreover, if it is to transition the research towards the next stage – Prescriptive Study, the aim at this stage is for the developed understanding to identify the potential for an improved reference model. The studies conducted at this stage are recommended by DRM as empirical data-collection methods (such as questionnaires, interviews and observations). Based on the specified principles of this stage, the descriptive stage of this thesis can be formulated as follows. By advancing the initial reference model for flexible fixture efficiency and design process, the partially identified efficiency description and design process will be tested, improved and completed. The outcome of this stage of this thesis is to establish the detailed features of efficiency and design-process understanding to enable a transition to the next stage. One way to realise the declared outcome is to design studies that incorporate the project requirements in terms of complete efficiency and a design model, as well as their partial descriptions defined in the previous stage. Furthermore, these studies may develop an appropriate flexible fixture using the existing body of knowledge. After development, observations may be made which allow conclusions to be drawn on a complete reference model. Accordingly, these studies will be represented by Publications A, B and C. At this stage, specific attention must be paid to the fact that the first two stages of the framework in Publications A and B appear in both studies. This is because the projects take more time and, thus, each publication can present the knowledge gained in relation to the requirements of both stages. Consequently, by executing this strategy by integrating these publications, Descriptive Study I will provide a complete understanding of *RQ*s 1 and 2.

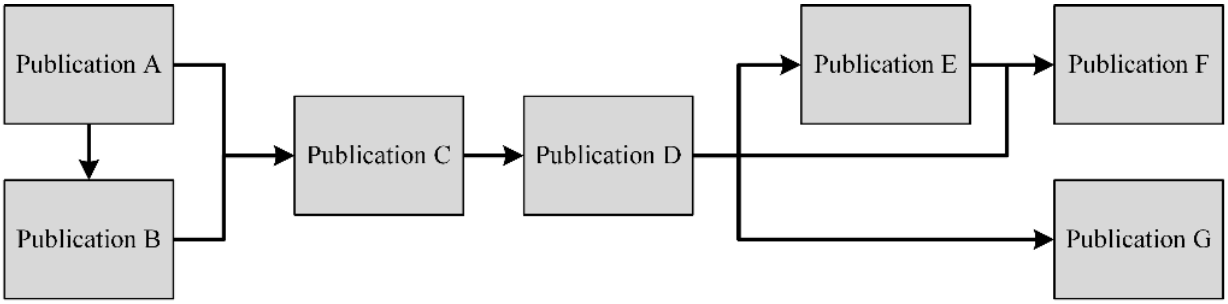
The third stage of DRM – Prescriptive Study – aims to elaborate upon and synthesise the outcome of Descriptive Study I and the knowledge generated in it. This stage realises a new impact model and supporting artefact based on the reference model, which describes an enhanced situation regarding the aim of the respective research. Moreover, it is important in the Prescriptive Study stage for the new model to be evaluated in respect of its consistency, completeness and functionality. The principles of this stage are incorporated into this thesis according to the following statements. A new design model synthesising the description and realisation of flexible fixture efficiency (*RQ* 1) in a systematic design process (*RQ* 2) is sought. Furthermore, the model is expected to identify and provide relevant background to enable full utilisation where active control of flexible fixtures is sought (*RQ* 3). Thus, it is possible to transition the developed model from a prescriptive stage to a descriptive one. The preceding statements will be realised in Publications D, E and F. Publication D will aim to synthesise the knowledge of previous publications and complete the efficiency description of flexible fixtures while operationalising the efficiency for use in a design process. Therefore, the answers to *RQ* 1 and *RQ* 2 need to be complete by the outcome of this stage. As the scope of *RQ* 3 is beyond this design, Publications E and F will seek to elaborate the aspects identified in Publication D and complete the answer to *RQ* 3. Consequently, by conducting the Prescriptive Study stage, this thesis will aim to deliver a new reference model containing the answers to all the research questions posed under the aims.

The final stage of DRM – Descriptive Study II – aims to use the outcome of the support and new impact model to evaluate whether the outcome has fulfilled its intended objective. In other words, this stage investigates whether the model solves or improves the existing phenomenon. The recommended focus for studies conducted in this stage is on applying the model in respect of an evaluation plan. The evaluation plan used for the studies aims to identify two aspects of the model; the first specialising in its applicability and the second evaluating usefulness. Once the principles of Descriptive Study II have been incorporated into the research of this thesis, a statement regarding application and success evaluation can be formulated as follows. The efficiency (*RQ* 1), design process (*RQ* 2) and active control (*RQ* 3) of flexible fixtures described in this thesis should be evaluated both internally and externally about their application. The internal evaluation may be described as the experiments conducted on the fixture artefacts in this thesis. Thus, the external evaluation describes the artefacts outside this thesis. This means the evaluation can be conducted retrospectively by this thesis on existing third-party fixtures, or prospectively and directly by third parties. The success evaluation, on the other hand, requires the developed fixtures to be implemented by third parties, using the knowledge contribution of this thesis to confirm the increased efficiency. This is industrial confirmation that the aim of this thesis has been realised.

With respect to the given formulation of Descriptive Study II into the research of this thesis, certain boundaries in relation to delimitations declaration in Chapter I need to be placed. Since the external evaluation of applicability and success for the knowledge generated by this thesis requires a level of data collection beyond its feasible capabilities, the delimitations regarding time and finance have been applied to this stage. Accordingly, the Descriptive Study II stage of the DRM will only be considered for an internal applicability evaluation. However, the effects of this will be discussed from verification and validation perspectives, with details presented in Sections 3.5 and 5.3. Thus, the publications in this study will seek to achieve experimental confirmation in respect of their aims, to prove that the proposed knowledge is functional and applicable. Hence, for the Prescriptive Study stage, Publications D, E and F will complement their model with experiments. Furthermore, Publication G will focus directly on the usability of Publication D via an internal evaluation. This will demonstrate certain key components of the model that are not directly evaluated in Publication D.

As the horizontal and vertical integration strategy of this thesis is specified, the individual building blocks (publications) will be governed by SDF principles. The main goal of SDF is to offer a framework that harmonises the cycle of observation/theory-building/experimentation. In so doing, the SDF proposes a four-step procedure. In the first step, the SDF proposes a state-of-the-art analysis. In the second step, determination of functionalities needed for the target system and execution of design and development are recommended. In the third step, a prototype is anticipated. Finally, experimentation or verification is conducted and observations made. This procedure is suitable for the individual publications in this thesis due to the independence of each publication, the content of which is also dependent on external projects. Based on this statement, the incorporation of the SDF into the publications may be done as follows. Firstly, each publication will conduct a literature review based on the target domain and input from the previous publication. Secondly, project requirements will be incorporated into the publications, if the publication is meant to report on the development carried out for a project. Thirdly, theoretical definitions or development cases will be given. Fourthly, the prototypes of development cases or experimentations will be presented. Finally, it is proposed that each publication will verify and reach conclusions that can be interpreted into a new study, to ensure that the adapted SDF can facilitate the requirements of the DRM.

Once an appropriate mapping of respective frameworks into the research of this thesis is established, a summary of the intended framework utilisation can be made. Each publication, as an individual artefact, uses the SDF to execute a specific research aim. In the multidimensional directions, this thesis aims to use DRM in which Publications A and B describe the Research Clarification stage. Publications A, B and C offer descriptive studies for the Descriptive Study I stage. A new reference model is presented in Publication D for the Prescriptive Study stage, based on the integration of previous publications. In addition, Publications E and F advance the new reference model in the Prescriptive Study stage. Finally, Publications D, E, F and G evaluate the reference model from an internal evaluation perspective and advance the new research into the Descriptive Study II stage. The information flow and DRM stages in respect of the publications in this thesis are illustrated in Figure 10.



Publications	RQ	Design Research Methodology: Research Clarification	Descriptive Study I	Prescriptive Study	Descriptive Study II: Internal	External
Publication A	1	●	●			
Publication B	1, 2	●	●			
Publication C	1, 2		●			
Publication D	1, 2			●	●	
Publication E	3			●	●	
Publication F	3			●	●	
Publication G	2				●	

Figure 10. Publications' knowledge flow and their use in respect of the DRM.

3.4.2 DATA COLLECTION

This section will elaborate on the data collection methods used in the publications regarding the frame utilisation classification of the previous section. Initially, this thesis proposes a distinction between two types of publications: project-driven and theory-driven. In the project-driven approach, a publication focuses on developing a fixture specific to the requirements of a project. Thus, fixture development is driven by project needs. In the theory-driven approach, a publication focuses on iterating the findings of previous publications for theory development purposes. These two approaches can interact with each other, as a theory-driven publication can be used for experimentation in an existing project or lead to a new one, whereas the findings of project-driven publications can be used to form theory.

In respect of the classification made, Publications A, B, C and G are project-driven and hence, their initial data collection stems from project requirements and theoretical needs. Specifically, Publication A reports on the Automated Process Control BiW project (AProC) in the automotive industry. Publications B and C describe the development conducted for Low Cost Manufacturing and Assembly of Composite and Hybrid Structures (LOCOMACHS), designed for the aerospace industry. Publication G demonstrates Robust and Effective Flexibility in Manufacturing Industries (REFMI). Publication D uses the findings of Publications A, B and C, the output of which is evaluated in Machine Optimisation Learning (MachOpt), within the automotive industry. Publications E and F are driven by Publication D's theoretical findings, whereas the individual theoretical findings of these publications are adapted to project SWE Demo. Without contradicting the SDF procedure, each publication, regardless of their approach, conducts the same specific data-collection methods, starting with literature reviews and theory-building. Moreover, each publication involves in an empirical study, either in the form of experimentation (for theory-driven publications) or prototype development (for project-driven publications) and followed by observational data-collection.

3.5 VERIFICATION AND VALIDITY

In order to evaluate the results of this thesis, appropriate definitions for verification and validity must be made since verification and validity can constitute different meanings in respect of a discipline's research approach. In positive sciences, the concepts of verification and validity do not constitute dominance so much as falsifiability and reproducibility [156]. Specifically, Popper [165] proposes that each artefact of scientific rigour needs to be reproducible, such that the outcome can be re-observed in different locations of time and space. Furthermore, it should be falsifiable, in that the artefact has clear and concise statements that can be tested.

However, in the social sciences, validity describes the credibility of results and meaningfulness and conclusions [154]. Cook and Campbell [166] describe four types of validity for quantitative studies: statistical conclusion, internal, construct and external, in order to reach a statement regarding the validity of the research. Statistical conclusion validity focuses on finding the relationship between different variables within a study where repeatable and accurate measurement of data is important from a reliability perspective [167]. Internal validity, on the other hand, focuses on the nature of this relationship and tests the effect of these variables on each other; also known as causality. Construct validity analyses the generalisation of individual studies in respect of the accuracy of the constructs that have been reached, with the concept of accuracy often benchmarked by a chain of evidence and triangulation [167, 168]. External validity advances the construct validity, depending on whether the generalisation can be expanded into a larger domain of time and space. In the qualitative territory of the social sciences, "trustworthiness, authenticity and credibility" are proposed as validity measurement methods by Creswell and Miller [168], whereas in design research the validity of qualitative research is conducted by identifying weakness and narrowing validity statements accordingly [157].

Contrary to Popper [165] falsifiability, Morse, et al. [169] propose verification as the process for consecutive checking and confirmation of the correctness of findings. This contributes to the validity of the research in the social sciences. In design research, the notion of verification is investigated by Buur [170] in respect of two methods, as there are many influencing factors which cannot easily be measured. The first verification method, verification by acceptance (or external verification), seeks confirmation of experts in the respective field. The second verification method, logical verification, evaluates the research based on its consistency, completeness, coherence and ability to reveal the research problem.

As differing verification and validity statements made in respect of the natural and social sciences, the strategy statement for this thesis will be made according to the pragmatic worldview declared in Section 3.2. Due to multidimensional nature of this research, with each publication following an experimental procedure on the horizontal axis and knowledge-building by generalisation on the vertical axis, both falsifiability and verification/validity definitions will be used in this thesis. This means that each publication is, itself, subject to falsifiability requirements, whereas verification and validity statements will be made for the research in this thesis, with the aim of answering the research questions. For the verification analysis, the abstract state of publications will be considered in relation to their contribution to this thesis. However, the validity analysis will be conducted in respect of the complete body of knowledge and the domain of each publication will be integrated, so as to reach a validity statement.

IV

RESULTS

This chapter aims to present an overview of the results, based on the appended publications. In so doing, each publication is presented as a summary of its sections: Description, aim, methodology, data collection method, results and conclusions.

4.1 RESULTS OVERVIEW

To facilitate easier understanding, this section will present an overview of the results in respect of the research questions posed in this thesis. Publication A presents the development of affordable reconfigurable fixtures for the automotive industry. The publication uses the available state-of-the-art fixturing approach and determines the capabilities and limitations of a production system in which time and cost constraints are dominant. At the same time, the limitations due to production system demands are also clarified by applying fundamental fixturing criteria. Consequently, Publication A takes the first step in providing an answer to *RQ* 1.

Based on the lessons learned from Publication A, a similar approach is used in Publication B for aerospace industries with automated reconfigurable fixtures. This publication further advances the determined criteria and elaborates on the answer to *RQ* 1. The publication starts by using a basic framework for flexible fixture design, using mechanical, control and in-process perspectives to create a foundation for *RQ* 2.

Publication C, moreover, presents a broader study by extending the learnings of Publication B in cooperation with other project members and using additional experimental data. This publication also contributes an additional four criteria to *RQ* 1. A more comprehensive design procedure is also proposed in this publication, to advance the results generated in Publication B in answer to *RQ* 2. Publication D aims to integrate the results generated in previous publications with extensive literature studies and formalise the answer to *RQ* 1. Alongside the determined criteria, the publication bridges *RQ* 1 and *RQ* 2 with relevant metrics measuring the efficiency of a designed fixture. Publication F also extends the description of quality criteria in Publication D and incorporates an active fixture control aspect into flexible fixture efficiency. For *RQ* 2, the publication presents a design procedure that starts with conceptual design and analysis stages, followed by detailed design and final verification. Finally, Publication D emphasises the need for a framework for active fixturing to complete the design procedure. Since active fixturing is associated with the use of flexible fixtures from a quality perspective, this publication also provides a bridge with *RQ* 3. Publication G demonstrates the application of the design procedure in *RQ* 2, regarding certain design steps. The publication also shows that the efficiency-oriented design of flexible fixtures can be enabled in a more enabling manner when an appropriate kinematic structure is available. This publication presents a novel parallel kinematic structure, called n-PRPR. It illustrates the advantages of using this structure in terms of kinematics, workspace, singularity and stiffness from a theoretical perspective.

Based on the conclusions of Publication D, two aspects of active fixturing, namely force and position control, have been identified in which *RQ* 3 can enhance the efficiency of flexible fixtures. Publication E presents a general oscillatory signal tracking controller based on the

Hilbert transform to establish a background for active fixtures’ position control. Subsequently, Publication F uses the controller framework of Publication E for position control, coupled with PD control, to create a general feedback/feedforward controller for active fixtures. Moreover, Publication F establishes force control in flexible fixtures. Consequently, Publications E and F complement *RQ* 2 by determining force and position control methods and answer *RQ* 3 by providing a generally applicable controller framework for using flexible fixtures. The publications and their contributions to the research questions are illustrated in a matrix in Table 2.

RQs		*RQ1*	*RQ2*	*RQ3*
PUBLICATIONS	**A**	Identifies criteria as: • Stiffness • Accuracy • Repeatability • Flexibility • Reconfiguration time • Deployment time • Cost		
	B	Identifies criteria as: • Reusability • Quality • Maintenance load • Process integration • Scalability & standardisation • Procurement time	Initiates design procedure as: • Mechanical (kinematic structure, standard/custom) • Control (motors, drives, PLC & safety systems) • Controller software (function groups related to process, fixturing and robotics)	
	C	Identifies criteria as: • Robotics capabilities • calibration • Knowledge demand • Controller independency	Elaborates design procedure: • Mechanical (kinematics position-holding) • Control system (motors/ drives, PLC/safety systems) • Controller software (robotics, process, fixture)	
	D	Finalises criteria with metrics as: • Fundamental • Flexibility (reconfigurability, reusability) • Cost (investment, setup) • Time (setup time) • Quality (diagnosability, reliability, convertibility)	Determines design procedure as: • Conceptual design and analysis • Conceptual verification • Detailed design and analysis • Final verification In addition to the criteria, certain technical metrics are incorporated into the design procedure.	

	E			Establishes a feedback/ feedforward position controller capable of tracking both periodic and non-periodic signals for universal use. The aim is to provide a background for active control of flexible fixtures.
	F	Extends quality criterion's diagnosability of Publication D in relation to active fixture control.	Elaborates the design procedure's active control as: • Position control • Force control ○ Direct force control ○ Indirect force control	Establishes the use of position and force control in single workpiece and assembly scenarios, in respect of process parameters, to increase the efficiency.
	G		Shows the applicability of the design procedure in Publication D by illustrating certain design steps. Shows that the efficiency-orientated design of flexible fixtures can be readily enabled when a suitable kinematic structure is available.	

Table 2. Results overview as publications and their contributions to RQs.

4.2 PUBLICATION A

Development of Affordable Reconfigurable Tooling in Car Manufacturing Cells - A Case Study

I. Erdem, H. Kihlman and A. Andersson, "Development of Affordable Reconfigurable Tooling in Car Manufacturing Cells – A Case Study", in ICPR23 International Conference on Production Research, 2015.

Description

This publication was written to facilitate fixture pick-up modification using case-based reasoning for BiW assemblies. This publication is a project-driven publication for AProC and focuses on the Research Clarification stage of the DRM with the SDF applied to the publication body. As the publication develops a flexible fixture and an evaluation procedure, a contribution to the Descriptive Study I stage is also made.

Aim

The aim of the study is to develop and apply a manual affordable reconfigurable tooling capable of satisfying pick-up location changes relating to the output of a case-based reasoning system and requirements of product changeovers.

Research approach

Firstly, this publication conducts a literature survey and establishes a design approach based on existing ART theory. Secondly, the project requirements are interpreted using a methodical development approach. This is based on the criteria that have been determined for the relevant workpiece and process in the project. Thirdly, a prototype fixture is designed and built to answer the requirements of the project. The prototype fixture is subsequently evaluated according to the specified requirements and overall observations regarding automotive manufacturing. The results are used and consolidated to clarify the description of efficiency.

Demonstrators/prototypes

Since this publication is driven by project needs, a prototype demonstrator for testing the functionality of a flexible fixture is demonstrated in this publication. Fundamental components of ART along with modular tools are developed to form the prototype demonstrator, which is illustrated in Figure 11.

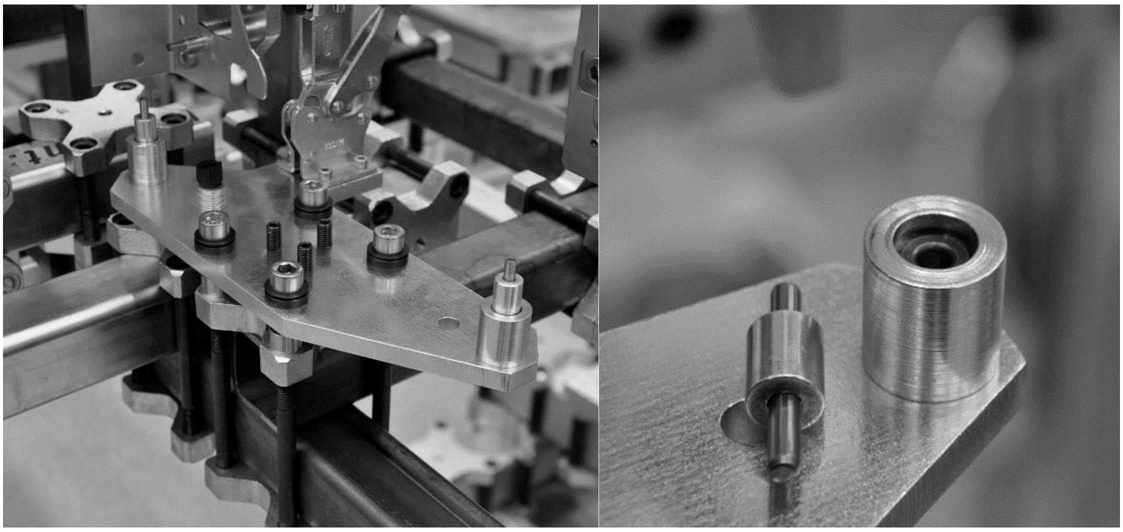


Figure 11. The ART demonstrator for AProC. Reconfigurable and modular fixture components are shown.

Results

As this publication offers initial clarification, the descriptive aspect of this publication offers a partial description of flexible fixture efficiency. This description determines that flexible fixture efficiency is influenced by the production system characteristics of the automotive industry, even though the stated project requirements focus only on technological capabilities. The publication describes influencing factors in terms of efficiency criteria so that a partial reference model can be established for Descriptive Study I. Thus, the efficiency description and relevant criteria contribute to answering *RQ 1*. The criteria identified in respect of the project requirements, theory used and production system characteristics are:

- **Stiffness**: the fixture's capacity to maintain its position or deflect within an acceptable range when subjected to process forces.
- **Accuracy:** the locational accuracy of fixture's locators in respect of a specific coordinate frame.
- **Repeatability:** the locator's capacity to secure the position of the workpiece within a tolerable range each time it is loaded.
- **Flexibility:** the physical capacity of the fixture to be configured according to the position and orientation of workpieces.
- **Reconfiguration time:** the time spent on fixture reconfiguration from one setup to the next.
- **Design and deployment time:** the time spent from the start of a fixture design to its deployment in a production system.

- **Capital cost:** the level of finance required for the fixture.

The publication discusses the existence of a compromise between the identified criteria, as they may affect each other negatively. Establishing a research clarification and reference model for Descriptive Study I requires that a procedure similar to the one in this publication should be applied to different types of flexible fixtures in production systems (other than the automotive industry).

Conclusions

Publication A uses an existing solution and clarifies the aim of this research. It shows that when fixtures are designed, the production system characteristics need consideration. This is because the absence of such consideration leads to gaps in understanding the compromise between different criteria. Hence, Publication A shows that the efficiency of a flexible fixture needs evaluation from a wider perspective.

4.3 PUBLICATION B

Development of Automated Flexible Tooling as Enabler in Wing Box Assembly

I. Erdem, P. Helgosson, and H. Kihlman, “Development of Automated Flexible Tooling as Enabler in Wing Box Assembly”, in Procedia CIRP, 2016, pp. 233-238.

Description

The publication is project-driven and presents the development of an automated Stewart platform (subsequently referred to as a hexapod) as a flexible fixture for the aerospace industry in a LOCOMAHCS project. The publication reveals the capacity of the developed hexapod as a fixture, plus an assembly robot using force-feedback.

This publication uses the conclusions of Publication A, aiming to test and elaborate upon the efficiency description and criteria under which flexible fixtures are expected to function within the aerospace industry. Thus, this publication participates in the Research Clarification and Descriptive Study I stages of the DRM.

Aim

The aim of this publication is to present the preliminary results on the flexible fixture developed according to the specific project requirements of the aerospace industry.

Research approach

Like the previous publication, this one begins with a literature survey of flexible fixtures in the aerospace industry, to establish a theoretical basis for the systematic design approach being used. Moreover, specific project requirements are incorporated into the flexible fixture domain. A prototype automated flexible fixture is then built using a partly disclosed design procedure, to answer the requirements of the project. The prototype fixture is subsequently evaluated in respect of the identified requirements and overall observations relating to aerospace manufacturing. The results are then consolidated to clarify the efficiency description and design procedure.

Demonstrators/prototypes

Similar to Publication A, this publication also presents a demonstrator-type prototype for evaluation purposes. The demonstrator is an automated flexible fixture in the kinematic form of a hexapod attached to modular fixture components. The workpiece used in this publication represents a wing assembly developed especially for force-feedback assembly, and is illustrated in Figure 12.

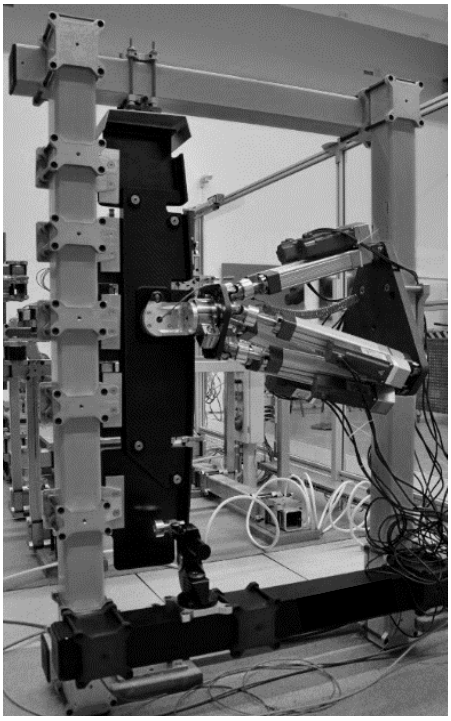


Figure 12. Hexapod demonstrator conducting force-feedback assembly.

Results

Based on the conclusions of Publication A, this publication focuses on the analysis of manufacturing paradigms by emphasising RMS and AMS. The features of these paradigms are then reflected onto the developed hexapod as capability requirements and identified as automation, sensor support and control system features. Moreover, the publication reaches to the criteria presented in Publication A for automated flexible fixtures – which confirms the applicability of stiffness, accuracy, repeatability, flexibility, capital cost, time to reconfigure and design/deploy. Thus, this publication contributes the following additional criteria to *RQ* 1:

- **Reusability:** a flexible fixture's suitability for multiple processes.
- **Quality:** a flexible fixture's negate or operate process variation.
- **Maintenance load:** the cost and time load of a flexible fixture in failure.
- **Process integration:** a flexible fixture's capability to be used in coordination with other technological constituents of the process.
- **Scalability & standardisation:** a flexible fixture's capability to be scaled using standardised hardware.

This publication also makes observations as to the nature of the determined criteria. It states that features added to satisfy criteria conflict with each other. Thus, this publication also confirms the findings of Publication A, that the efficiency criteria for flexible fixtures need to be captured while considering the trade-offs.

In addition to determining criteria and its contribution to *RQ* 1, this publication also lays the foundation of a design approach by dividing the development into groups of mechanical, control and controller software, with the active control of flexible fixtures integrated into software design as an additional means of meeting quality requirements. Hence, an initial design approach in answer to *RQ* 2 is established by this publication. Therefore, the Research Clarification stage for *RQ* 2 is accomplished.

Conclusions

This publication concludes that in developing flexible fixtures, the requirements of a production system play an important role in the design of flexible fixtures. However, a standardised design approach may be achieved when this role is considered critically in terms of criteria in the development of flexible fixtures. Similar to Publication A, this publication also elaborates on the conflicting nature of different criteria, showing that different requirements may affect each other negatively.

4.4 PUBLICATION C

Automated Flexible Tooling for Wing Box Assembly: Hexapod Development Study

I. Erdem, P. Helgosson, A. Gomes and M. Engström, “Automated Flexible Tooling for Wing Box Assembly: Hexapod Development Study”, in SAE Technical Paper 2016-01-2110, 2016.

Description

This publication is driven by a LOCOMACHS project. It extends the study in Publication B and presents the results of the hexapod development. The publication thus combines the efforts of multiple types of flexible fixtures used in this project to methodically describe the development process, while deepening the methods and criteria as compared to Publication B.

As advancing the efficiency description and criteria based on an extended study, this publication is designed to complete the partially built reference model from Publications A and B. Therefore, the Descriptive Study I stage is completed using reference models for efficiency description with their respective criteria (*RQ* 1) and design procedure for flexible fixtures (*RQ* 2).

Aim

The paper aims to show the results of flexible fixturing development, guided by a new-build philosophy to meet the demands of a reconfigurable manufacturing paradigm.

Research approach

Starting with a literature review, an analysis is presented of the new-build philosophy and targeted manufacturing paradigm. The analysis synthesises the knowledge generated by Publications A and B in terms of design criteria and design procedure with further developments achieved by this publication. Furthermore, for completeness and accuracy purposes, the reference model describing efficiency criteria and design process are evaluated in respect of multiple flexible fixtures developed by other project members. Moreover, a comprehensive demonstrator is developed to evaluate the fitness of the fixtures developed for the reference model.

Demonstrators/prototypes

A demonstrator is developed for evaluation purposes. This comprises multiple types of hexapods working, in coordination with other process robots, on the assembly of a wing box. The demonstrator is located at the Manufacturing Technology Centre (MTC) in Coventry, United Kingdom and is illustrated in Figure 13.

Figure 13. The demonstrator site comprising two types of hexapods and process robots at the MTC.

Results

Like Publication B, this publication extends the analysis based on RMS in relation to new-build philosophy and multiple fixtures. This analysis shows that the efficiency description (relating to fitness according to a set of requirements operationalised by relevant criteria) remains accurate in relation to this extended study. Moreover, the extended study, which uses a broader scale of flexible fixtures, brings additional capabilities to improve the answer to *RQ* 1. These determined criteria are given as:

- **Robotics capabilities:** similar to standard industrial robots, automated flexible fixtures are also expected to have programming features such as motion planning, error handling and coordinating frame transformation.
- **Controller independence:** the controller capacity for use with different fixturing devices.
- **Effective calibration:** the flexible fixture's capability to calibrate itself without requiring external measurement units. This is because external resources create a conflict between accuracy and cost.
- **Knowledge demand:** the ease of learning of an automated flexible fixture from the operator's perspective, as replacement of a manual device with an automated solution may need extra learning activities.

This publication also contributes to *RQ 2* by extending the mechanical, control and controller software approaches with a product development approach. In mechanical design, the development procedure is initiated and directly related to a kinematic structure. This allows a systematic selection process for mechanical components. Hence, the study determines the individual components in the kinematic structure whether they are standardized and custom, and facilitates a link between cost, standardisation and scalability and kinematic structure. Thus, the publication proposes (from a mechanical point of view) a fundamental reference model on the interaction of criteria, characteristics and the developed flexible fixture.

As for control hardware, the publication identifies standard components that can be used in the design procedure. The study determines maps and identifies standard components and custom functionalities that each flexible fixture can have. The publication states that drives, motors, programmable logic controllers (PLC) and safety systems are standard components. However, due to differing demands on each system and the individual regulations for each production system, the publication states that the control hardware design may remain relatively unique compared to mechanical design. Therefore, when conducting a detailed design of flexible fixtures, control components other than the standard ones require individual analysis.

In controller software design, the publication uses function groups and their suggested solutions in similar fashion to product development. By using this method, the publication sets a framework for controller software for flexible fixtures. This framework comprises function groups that are process-related, fixturing-related and robotics-related. As all aspects of design are determined according to the collection of specific criteria, this publication contributes to *RQ 2*, in that the criteria relating to the efficiency of flexible fixtures can be used in the conceptual design stages and relevant solutions selected accordingly. Consequently, the publication shows an integration method allowing efficiency criteria to be used directly in the design process. They are integrated into a direct design, either as physical objects or as function groups in the software.

Conclusions

This publication concludes that correlating the design procedure to process and manufacturing paradigm requirements allows the design of more efficient flexible fixtures. Describing capabilities as function groups in conceptual development stages is shown to be an effective tool in realising efficiency-oriented flexible fixtures, with the trade-offs between different criteria mitigated early in the design process. Thus, a methodical approach that comprehensively considers both efficiency criteria and design processes can help flexible fixtures fit into their production systems, rather than adapting the production system to flexible fixtures.

4.5 PUBLICATION D

A novel comparative design procedure for reconfigurable assembly fixtures

I. Erdem, C. Levandowski, C. Berlin, H. Kihlman, and J. Stahre, “A novel comparative design procedure for reconfigurable assembly fixtures”, *CIRP Journal of Manufacturing Science and Technology*, vol. 19, pp. 93-105, 2017/11/01/ 2017.

Description

Publication D is driven by theory and plays an important role in terms of combining the previously determined criteria and development knowledge from Publications A, B and C. This publication’s entire focus is to collect and complete the efficiency description by means of criteria – which provides the answer for *RQ* 1 – and establishing a design procedure for use as a new impact model in answering *RQ* 2. Accordingly, the publication bridges between the efficiency criteria and the design procedure by operationalising the criteria in terms of metrics and embedding them directly into the design procedure.

In proposing a new design procedure with operationalised criteria metrics, this publication conducts a prescriptive study and offers a novel approach to flexible fixture design. Moreover, the publication paves the way for active control of flexible fixtures, which transitions the research of this thesis from *RQ* 2 to *RQ* 3. Finally, the publication details an experiment conducted to demonstrate the applicability of the new impact model. This is the publication's contribution to the internal evaluation stage of Descriptive Study II.

Aim

The aim of this publication is to propose a design procedure that unifies mechanical, control and software aspects of flexible fixture development, whilst evaluating the solutions comparatively in terms of their fitness for a production system from an efficiency perspective.

Research approach

The publication asks two research questions, similar to *RQ* 1 and *RQ* 2 of this thesis. The answers to these are investigated by means of a literature survey and theoretical development. Data gathering in this publication is realised via an experimental study that verifies the applicability of the design procedure and efficiency criteria.

Experiments

An experimental study is conducted to exemplify and verify the metrics and design procedure where Tsai manipulator and Cartesian units as flexible fixture concepts are conceptually developed for the automotive industry. The comparison between the two possible solutions is shown and detailed design is conducted on the Cartesian unit, due to its greater efficiency in the relevant production system. The experiment is illustrated in Figure 14.

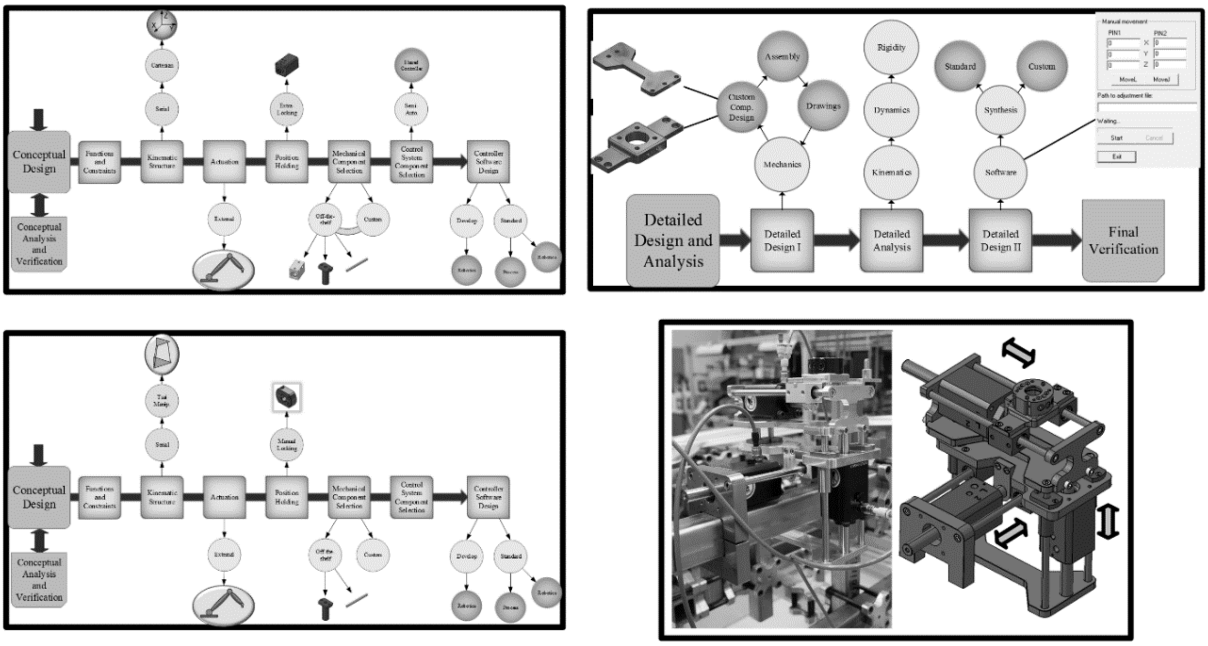


Figure 14. The experiment conducted in Publication D with a Cartesian flexible fixture.

Results

In order to answer *RQ* 1, the publication initially establishes a correlation with PMS and its performance indicators. It also adapts cost, time, quality and flexibility indicators as flexible fixture design parameters as follows:

- **Flexibility**: physical adaptability of a flexible fixture to various products and processes
- **Cost**: total investment and running cost of a flexible fixture
- **Time**: the amount of time needed for use of a flexible fixture

- **Quality**: the process' robustness, achieved by the use of a flexible fixture.

Furthermore, the publication offers a distinction between flexible fixture efficiency criteria and parameters, by defining criteria as the operationalisation of parameters towards developing relevant quantifiable metrics. Thus, the publication offers the following criteria to operationalise flexibility:

- *Reconfigurability*: physical ability to adapt products in a product family.
- *Reusability*: physical ability to adapt multiple processes.
- *Modularity*: physical ability of a fixture to be rebuilt for multiple products and processes, using standardised components.

The cost parameters are operationalised by these criteria:

- *Investment cost*: investment capital needed for a flexible fixture's hardware and software.
- *Setup cost*: investment required to set up a flexible fixture's hardware and software.

The time parameter is operationalised as follows:

- *Setup time*: time required to finalise the setup operation for a flexible fixture.

Quality parameter is complemented by these criteria:

- *Diagnosability*: ability of a flexible fixture to exchange information regarding process parameters.
- *Reliability*: reliability of standard components within a flexible fixture, from a maintenance perspective.
- *Convertibility*: ability of a flexible fixture to complement, or interact with, external technologies and tools.

In addition, the publication incorporates the knowledge generated by previous publications and general fixturing theory, by introducing fundamental fixturing criteria:

- *Weight:* total weight of a flexible fixture.
- *Dimensions:* minimum fundamental dimensions of a flexible fixture.
- *Stiffness*: ability of a flexible fixture to withstand occurring forces.
- *Accuracy:* accuracy of a flexible fixture when reaching a target position.
- *Repeatability:* repeatability of a flexible fixture while locating a position and a workpiece.

With the criteria for individual parameters established, the publication makes a distinction between fundamental criteria and whether they vary according to process requirements. Thus, stiffness, accuracy and repeatability criteria are incorporated into reusability. Subsequently, the remaining criteria are expressed via an anticipated state. This is done by defining an equation that yields a ratio between production system requirements and the resulting value of a criterion in the developed fixture. The publication thus quantifies the fitness of a developed solution to a production system and expresses this fitness ratio as flexible fixture efficiency. Finally, the efficiency results of each metric are weight-averaged to define a final efficiency value. This allows different metrics to be synthesised according to the demands of a production system. The metrics describing the anticipated state of each criterion are given in Table 3.

Table 3. The metrics and their definitions for each efficiency criterion.

Efficiency metric	*Definition*	*Efficiency equation* (ε_i)
Weight (W_c)	W_a: Flexible fixture weight. W_T: Maximum weight allocated to the flexible fixture.	$W_c = 1 - \frac{W_a}{W_T}$
Dimensions (V_c)	V_a: Flexible fixture volume (based on the dimensions). V_T: Maximum volume allocated to the flexible fixture.	$V_c = 1 - \frac{V_a}{V_T}$
Reconfigurability (R_c)	P_a: The number of products within the workspace of a flexible fixture. P_T: Anticipated number of products that a flexible fixture should satisfy.	$Rc_c = \frac{P_a}{P_T}$
Reusability (Re_c)	Pr_T: The number of processes satisfied by a flexible fixture. P_{ra}: Anticipated number of processes that a flexible fixture should satisfy.	$Ru_c = \frac{Pr_a}{Pr_T}$
Modularity (M_c)	N_s: The number of standard components in a flexible fixture. N_T: The total number of components in a flexible fixture.	$M_c = \frac{N_s}{N_T}$
Cost	C_f: Hardware cost of a flexible fixture. C_e: Cost of setup and external equipment needed for a flexible fixture. C_s: The software development cost with C_{wh} as cost per hour and T_A as the software development time. C_T: The total cost allocated to a flexible fixture.	$C_c = 1 - \frac{C_f + C_e + C_s}{C_T}$ $(C_s = C_{wh}T_A)$
Time (T_c)	T_s: The total setup time required for a flexible fixture. T_t: The total setup time allocated to a flexible fixture.	$T_c = 1 - \frac{T_s}{T_t}$
Diagnosability (D_c)	The binary value describing diagnosability: 1 for capable and 0 for not capable.	$D_c = 1 \text{ or } 0$
Reliability (Re_c)	Re_i: Reliability of each standard component. Re_t: The total reliability requirement for the flexible fixture.	$Re_c = \frac{\prod_i Re_i}{Re_t}$
Convertibility (Co_c)	Binary value describing convertibility: 1 for convertible and 0 for not convertible.	$Co_c = 1 \text{ or } 0$
Final efficiency	*Weight-averaged efficiency, in which weights are determined according to the needs of a production system.* ε_i*: Each efficiency metric as defined above.*	$\varepsilon_o = \frac{\sum_i^{10} \varepsilon_i w_i}{\sum w_i}$

The design procedure presented in this publication aims to provide a new impact model and an answer to *RQ* 2. Thus, the publication develops a design procedure that treats the developed metrics as design constraints and integrates them into four design stages. These stages are determined by the publication as follows. The first stage, Conceptual Design and Analysis, comprises seven steps spanning from mechanical control to software aspects. These allow a designer to evaluate possible flexible fixture solutions without spending excessive amounts of time on design. The conceptual design steps are:

- *Thresholds for functions and constraints:* the target production system is analysed, and relevant thresholds are determined for efficiency metrics.
- *Kinematic structure:* different kinematic structures are proposed for evaluation. The need for kinematic classification to standardise the procedure is emphasised.
- *Actuation:* the type of actuation used by the flexible fixture. Internal actuation is self-actuated flexible fixture such as a robot, whereas external actuation describes manipulation by a different automated resource, such as a human or a process robot.
- *Position-holding:* describes the type of mechanism securing a flexible fixture to a target position. The position-holding can be achieved by a human (manual locking), an external lock mechanism whether standard or custom-made (extra-locking), or internally by a power source such as motor/brakes and hydraulic pistons (intra-locking).
- *Mechanical component selection:* two types of components can be selected for conceptual design. These are off-the-shelf (standard) and custom. The designer's knowledge and component library play an important role in this step.
- *Control system component selection:* initially, a flexible fixture controller is divided into semi and fully automated. A semi-automated control system implies that the flexible fixture's control is realised by either an external automation tool, such as a process robot or stand-alone system controlling multiple fixtures. The fully automated control system describes a dedicated control for each flexible fixture.
- *Controller software design:* an initial classification is made in respect of standard and custom features in the controller software. In the standard components, a flexible fixture is expected to have robotics (such as jogging) and process-related functions (such as communications). The custom features are categorised as active fixturing (such as workpiece-specific force control) and robotics (such as kinematics and dynamics).

The conceptual verification stage offers a comparative efficiency measurement (using Table 3) between multiple flexible fixture proposals and thus determines the most promising solution. In this stage, the metrics are measured conceptually via certain estimation rules. All metrics except reconfigurability and reusability are calculated based on the selected components and features, while reconfigurability is suggested based on a conceptual workspace computation. Reusability calculation is based on the requirement that the kinematic structure and actuation/position-holding components used have a relevant meta-model of stiffness, accuracy and repeatability.

Next, a detailed design stage is proposed, based on the conceptual verification. The following steps are suggested in this stage:

- *Detailed design I.* In this step, detailed mechanical and control system designs are conducted. Mechanical design comprises custom components and assembly design, including standard components. Control system design comprises electrical circuitry and a control box. The outcome of this step is drawings describing the details of the relevant flexible fixture.
- *Detailed analysis.* The flexible fixture's mechanical analysis is conducted in respect of kinematics, dynamics, singularity and rigidity (stiffness).
- *Detailed design II.* This step involves designing detailed software, including a graphical user interface and synthesis of conceptual software components.

In the last stage, final verification, an efficiency measurement of the developed fixture is conducted iteratively, to improve the overall efficiency of the relevant flexible fixture. As with the second stage, the metrics from Table 3 are used.

In addition, the publication discusses the lack of active fixturing control methods for flexible fixtures that would increase the applicability of the proposed design procedure and efficiency metrics. Not only limited to the applicability of the proposed design procedure but also the overall efficiency of flexible fixtures can be increased, as their contribution to process quality would drive flexible fixtures to be more competitive in relation to their counterparts (dedicated fixtures).

Since this publication offers a description of efficiency criteria and novel metrics integrated into a comparative design procedure, a new impact model for the Prescriptive Study stage is realised. Due to the applicability experiments conducted within the publication, a descriptive study is also realised for internal evaluation in the Descriptive Study II stage of the DRM. By analysing the active control of flexible fixtures, the publication identifies a lack of standardised control approaches to flexible fixtures. Thus, a bridge to a deepened impact model and *RQ* 3 is also established.

Conclusions

This publication concludes that the efficiency of flexible fixtures can be conceptually verified; and design steps can be taken accordingly. The comparative nature of the design procedure allows fixture designers to determine the most suitable solution and iteratively increase the efficiency of a detailed design.

4.6 PUBLICATION E

Feedforward control for oscillatory signal tracking using Hilbert transform

I. Erdem, G. Asbjörnsson, H. Kihlman, "Feedforward control for oscillatory signal tracking using Hilbert transform", *European Journal of Control*, 2019/06/11/ 2019.

Description

Publication E is theory-driven and presents a novel theory on tracking oscillatory signals for general use in control systems. The publication focuses on details of a control system approach that enables linear and stable processes to track any oscillatory input using the Hilbert transform (HT) and feedforward control. The theory of oscillation tracking presented in this publication is connected to the need for flexible fixtures that compensate and stabilise when subjected to periodic signals, whether force or position. Thus, this publication investigates the theoretical input received from Publication D in relation to *RQ* 3. Since the theory that is developed has applicability beyond flexible fixtures, the body of knowledge it creates is presented as an independent control approach.

By establishing the background for position control of flexible fixtures, this publication contributes to RQ 3. It also comprises a prescriptive study to improve the reference model given in Publication D. Moreover, the publication comprises experiments by way of a descriptive study for the internal evaluation aspect of Descriptive Study II.

Aim

This publication aims to create a control system foundation for fixture utilisation, as they are subjected to oscillatory signals. Due to its previously stated potential, the publication addresses a general audience with the stated aim of presenting a feedforward controller. It uses Hilbert analysis to generate a feedforward signal, by measuring both input and output signals.

Research approach

The publication includes a literature survey on control theory, developed for systems that are subject to various oscillatory disturbances. These include robotic manipulators, structures subject to earthquakes, payload control for cranes with flexible cabling, and oceanic structures compensating for wave motion. In addition, the literature survey also extends to various oscillatory signal analysis methods, including Fast Fourier Transform (FFT), wavelet transform and HT, while describing the advantages of HT over the remaining methods regarding its suitability in control systems. Based on the literature survey, the publication presents the proposed feedforward control theory and conducts simulation experiments demonstrating the efficiency of the controller.

Experiments

The publication conducts simulation experiments on a second-order process by using multicomponent, decaying FM and AM signals. Furthermore, model error correction is verified under a multicomponent signal. All experiments are conducted in respect of an existing feedback controller, to demonstrate the effectiveness of the controller. The results of simulation experiments are illustrated in Figure 15.

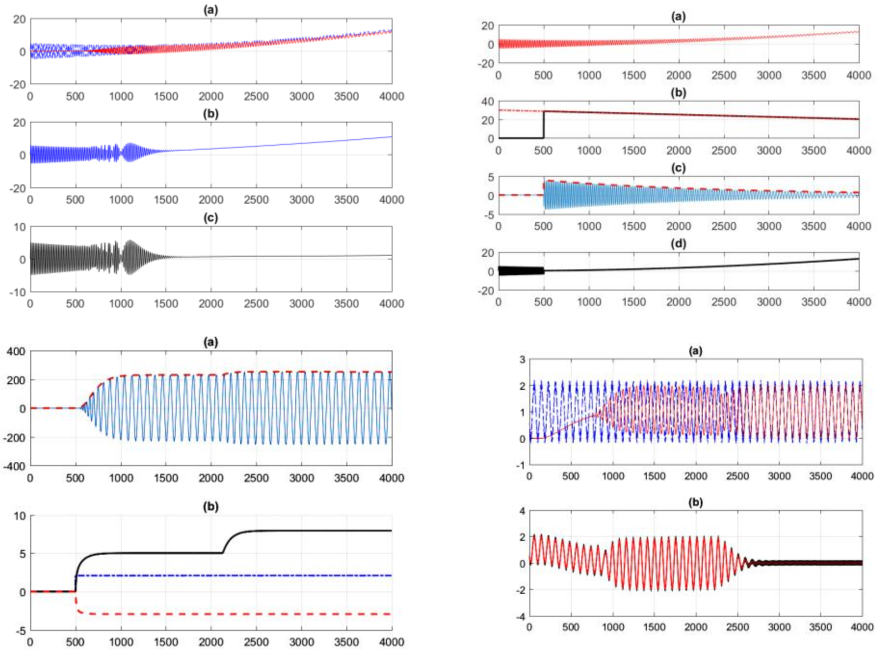


Figure 15. Feedforward control with Hilbert transform and an excerpt from the publication's experiments.

Results

The proposed controller's initial premise relies on a predictive oscillatory signal based on the measurements conducted on both input and output signals to determine amplitude, frequency and phase contents. The analysis is initiated by applying HT to an input signal $x(t)$:

$$x_h = PV \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{x}{t - \tau} d\tau \tag{1}$$

where PV is the Cauchy principal value and x_h is a phase-shifted signal. By using $\hat{x} = x + ix_h$, an analytical signal $\hat{x}$ is generated. By virtue of $\hat{x}(t) = a(t)\, e^{i\phi(t)}$ with $a(t)$ and $\phi(t)$ as the instantaneous envelope and phase of the signal, the relevant content of the oscillatory signal is generated. Thus, the frequency (w) of the input signal is determined by $w = d\phi/dt$.

By applying the same analysis to the process output, the process's phase distortion (Δ_τ) and amplitude attenuation (Δ_a) in respect of the input signal are determined. Using the input signal content, a feedforward signal is generated, the phase and amplitude of which are shifted and amplified in respect of the process attenuation and delay. The feedforward signal (C_{ff}) is:

$$C_{ff} = \Delta_a A_d \cos(w_i t + \phi_i + \Delta_\tau). \tag{2}$$

Furthermore, the changes in the process are constantly reflected on the feedforward signal. Thus, a continuous oscillation tracking is achieved. Moreover, the drawbacks of system inversion and elaborate model identification methods are eliminated using the proposed controller strategy. The feedforward signal generation in relation to a feedback controller is shown schematically in Figure 16.

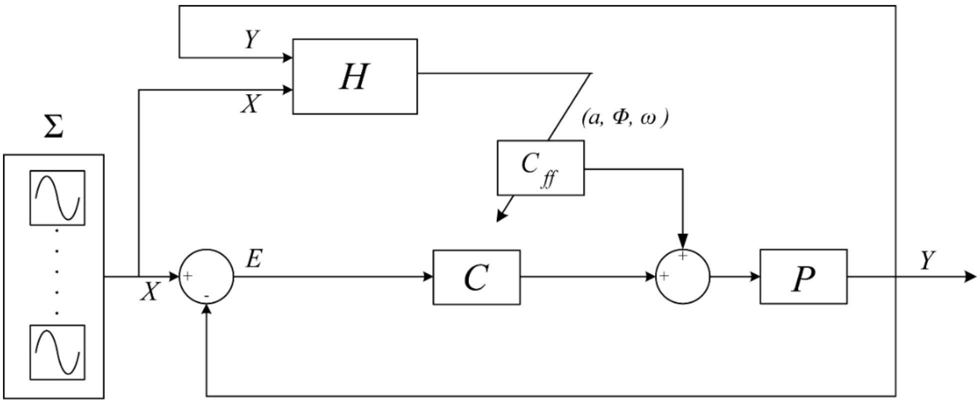


Figure 16. The HT-based feedforward controller in a typical feedback controller.

Consequently, a typical feedback controller is given the capacity to track or take various actions under an oscillatory signal. The publication also shows that performance under non-periodic signals is not affected, with the feedforward control only interacting with oscillatory signals due to HT's properties. Subsequently, the controller uses the analytical properties of Hilbert analysis; these can identify multicomponent, stationary and nonstationary signals. This, in turn, enables the system to maintain its performance for various applications, including various mechanical systems. Finally, this publication establishes a bridge to *RQ* 3 as it provides the necessary background for how flexible fixture control systems can be actively controlled when fixtures are subjected to oscillatory signals. A prescriptive study is therefore presented and internally evaluated for the Descriptive Study II stage of the DRM.

Conclusions

This publication shows that by using an input and output relationship, any stable process can be regulated to track oscillatory signals. Within this relationship, the input signals can be both position and force, as long as appropriate relationships are established. In a fixturing context, this statement can be interpreted as meaning that any fixturing device can be controlled to compensate for vibratory position signals. Consequently, the foundation for fixture position regulation can be established by using the proposed feedforward controller.

4.7 PUBLICATION F

Workpiece Force and Position Control for Active and Flexible Fixtures

I. Erdem, G. Asbjörnsson, H. Kihlman, "Workpiece Force and Position Control for Active and Flexible Fixtures", *The International Journal of Advanced Manufacturing Technology*, 2019. (Submitted).

Description

Publication F is theory-driven and presents an active control framework for flexible fixtures, correlating the process quality and robustness to the regulation of force and the position disturbances to process nominals. The results of this publication extend Publication D's quality criterion and establish the answer to *RQ* 3. This complements the active control term of the design procedure's controller in detail. In addition, this publication uses the controller developed in Publication E for oscillatory position regulation in flexible fixtures.

Thus, the publication contributes to this thesis by conducting a prescriptive study in which the new impact model is completed. Furthermore, the publication conducts experiments for the internal evaluation of the Descriptive Study II stage.

Aim

The aim of this publication is to present an active control system for flexible fixtures, covering force and position control in single workpiece and assembly scenarios.

Research approach

As with previous publications, this study begins with a minor literature survey (on existing fixture theory) to show the lack of general control strategies for fixtures. Following the literature analysis, a system for modelling fixture dynamics is presented, which adapts standard manipulator dynamics. Furthermore, different control strategies are developed (position, direct and indirect force control). Finally, stability analysis and experiments are conducted to prove the applicability of the active control system.

Experiments

The experiments are conducted to evaluate the proposed force control strategies using the hexapod presented in Publications C and D. Since Publication E conducts experiments similar to those for position control, the experiments in this publication are limited to force control. In these experiments, different control parameters are tested for their performance in force control strategies. The experimental setup is presented in Figure 17.

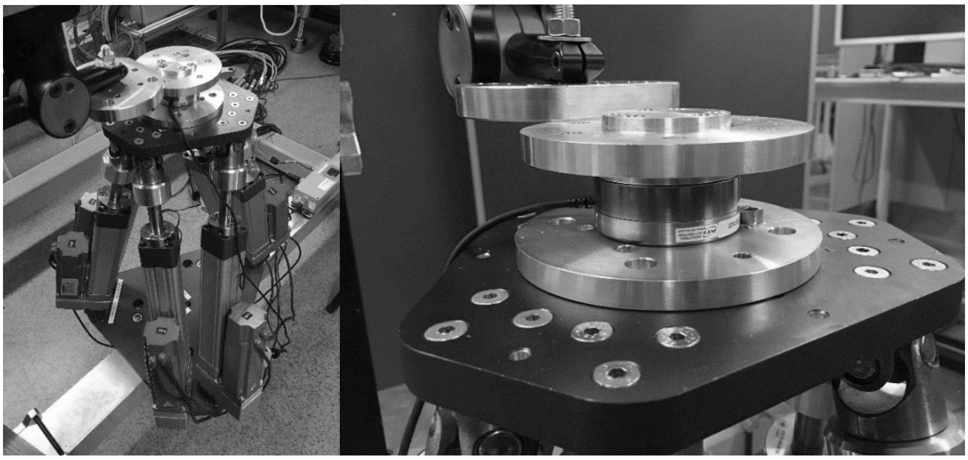


Figure 17. Experimental setup using the hexapod for force control.

Results

The results presented in this publication provide an answer to *RQ* 3, as force and position control are two ways of having active control in flexible fixtures. Thus, the term “active control” is described as the capacity of a flexible fixture to maintain process nominals during disturbances. Hence, the efficiency criterion “diagnosability” in Publication D remains in accordance with active control. This is because an active controller inherently yields 1 for the diagnosability metric. As with fixtures interacting with their environments, a general system model illustrated in Figure 18 is presented to establish the relevant control strategies.

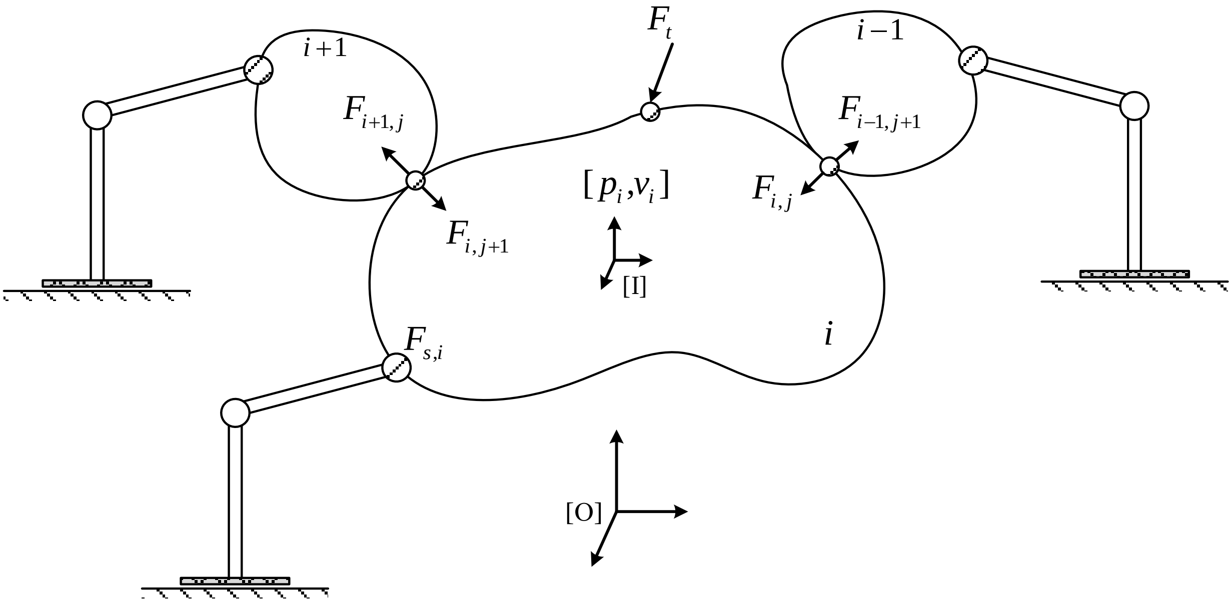


Figure 18. Model of an assembly of workpieces manipulated by active fixtures.

A workpiece-oriented active control strategy is then established, in which contact forces acting on the workpiece are described via the standard model as follows:

$$\mathbf{M_i}\dot{\mathbf{v}}_\mathbf{i} + \mathbf{C}(\mathbf{p_i}, \mathbf{v_i})\mathbf{v_i} + \mathbf{G}(\mathbf{p_i}) + \sum_{\mathrm{j}=\mathbf{1}}^{\mathrm{m}} \mathbf{F_{i,j}} = \mathbf{F_{s,i}} \tag{3}$$

where $\mathbf{C}$ and $\mathbf{G}$ are the Coriolis-centrifugal and gravitational forces. $\mathbf{F_{i,j}}$ is the force and moment vector exerted at a contact node. By using the workpiece model, the dynamic model for a flexible fixture and its workpiece is described as:

$$\widehat{\mathbf{\Lambda}}_\mathbf{i}\dot{\mathbf{v}}_\mathbf{m,i} + \widehat{\mathbf{C}}_\mathbf{i}\mathbf{v_{m,i}} + \widehat{\mathbf{G}}_\mathbf{i} = \mathbf{F_{m,i}} - \mathbf{F_{i,j}}^{\mathbf{\Sigma}} \tag{4}$$

where $\mathbf{F_{m,i}}$ is the control input and $\widehat{\mathbf{\Lambda}}_\mathbf{i} = \mathbf{\Lambda_i} + \mathbf{M_i}$, $\widehat{\mathbf{C}}_\mathbf{i} = \mathbf{\Gamma_i} + \mathbf{C_i}$ and $\widehat{\mathbf{G}}_\mathbf{i} = \mathbf{B_i} + \mathbf{G_i}$ are the combined fixture and workpiece mass, Coriolis-centrifugal and gravitational forces. Following the system formulation, active fixture control strategies are presented as follows:

- **Direct force control**: the capability of flexible fixtures to regulate the sum of contact forces with respect to desired process parameters.

This control strategy is formulated in respect of direct contact force errors in the assembly. The performance of the proposed controller when there is no contact is also evaluated. The direct control is formulated by the publication with respect to a force error $\mathbf{e_f} = \mathbf{F_{i,j}}^{\mathbf{d}} - \mathbf{F_{i,j}}^{\mathbf{\Sigma}}$ where $\mathbf{F_{i,j}}^{\mathbf{d}}$ is the desired contact force as follows:

$$\mathbf{F}_{\mathbf{m},\mathbf{i}} = \widehat{\boldsymbol{\Lambda}}_{\mathbf{i}}\left(-\mathbf{K}_{\mathbf{d}}\, \mathbf{v}_{\mathbf{m},\mathbf{i}} + \mathbf{K}_{\mathbf{p}}\mathbf{K}_{\mathbf{e}}^{-1}\mathbf{e}_{\mathbf{f}}\right) + \mathbf{F}_{\mathbf{i}}{}^{\mathbf{d}} + \widehat{\mathbf{C}}_{\mathbf{i}}\mathbf{v}_{\mathbf{m},\mathbf{i}} + \widehat{\mathbf{G}}_{\mathbf{i}} \tag{5}$$

where $\mathbf{K_d}$ and $\mathbf{K_p}$ are (6x6) positive definite gain matrices.

- **Indirect force control**: the capability of flexible fixtures to exhibit a second-order system, such as in admittance control.

This control strategy emphasises the use of flexible fixtures when they are subjected to forces arising from a process, such as drilling. The proposed admittance control enables flexible fixtures to conform to force errors in respect of a predetermined second-order system. The indirect control is described by:

$$\mathbf{F}_{\mathbf{m},\mathbf{i}} = \widehat{\boldsymbol{\Lambda}}_{\mathbf{i}}\left(\dot{\mathbf{v}}_{\mathbf{c},\mathbf{i}} + \mathbf{K}_{\mathbf{d}}\dot{\mathbf{e}}_{\mathbf{cm},\mathbf{i}} - \mathbf{K}_{\mathbf{m}}\mathbf{e}_{\mathbf{cm},\mathbf{i}}\right) + \mathbf{F}_{\mathbf{i},\mathbf{j}}{}^{\boldsymbol{\Sigma}} + \widehat{\mathbf{C}}_{\mathbf{i}}\mathbf{v}_{\mathbf{m},\mathbf{i}} + \widehat{\mathbf{G}}_{\mathbf{i}} \tag{6}$$

where $\mathbf{e}_{\mathbf{cm},\mathbf{i}} = \mathbf{p}_{\mathbf{c},\mathbf{i}} - \mathbf{p}_{\mathbf{m},\mathbf{i}}$ and $\mathbf{p}_{\mathbf{c},\mathbf{i}}$ is the position of a compliance frame $[\mathbf{C}]$ and where $\mathbf{p}_{\mathbf{c},\mathbf{i}}$ is calculated with mass($\mathbf{M}_{\mathbf{mc}}$), damping $\mathbf{K}_{\mathbf{dc}}$ and stiffness ($\mathbf{K}_{\mathbf{mc}}$) parameters via a standard integration in respect of a desired trajectory:

$$\mathbf{M}_{\mathbf{mc}}\left(\dot{\mathbf{v}}_{\mathbf{d},\mathbf{i}} - \dot{\mathbf{v}}_{\mathbf{c},\mathbf{i}}\right) + \mathbf{K}_{\mathbf{dc}}\left(\mathbf{v}_{\mathbf{d},\mathbf{i}} - \mathbf{v}_{\mathbf{c},\mathbf{i}}\right) + \mathbf{K}_{\mathbf{mc}}\left(\mathbf{p}_{\mathbf{d},\mathbf{i}} - \mathbf{p}_{\mathbf{c},\mathbf{i}}\right) = \mathbf{e}_{\mathbf{f}} \tag{7}$$

Unlike the direct force control, this control strategy maintains the given reference position or trajectory. This allows flexible fixtures to exhibit compliance, for both tracking and regulation purposes.

- **Position control**: the capability of flexible fixtures to regulate their position in respect of periodic and non-periodic disturbances.

This control strategy integrates Publication E with a standard feedback controller to correspond to error signals. The position control input for both oscillatory and non-periodic error input is:

$$\mathbf{F}_{\mathbf{m},\mathbf{i}} = \left(-\mathbf{K}_{\mathbf{d}}\dot{\mathbf{e}}_{\mathbf{dm},\mathbf{i}} + \mathbf{K}_{\mathbf{p}}\mathbf{e}_{\mathbf{dm},\mathbf{i}}\right) + \mathbf{C}_{\mathbf{ff}} + \mathbf{F}_{\mathbf{i},\mathbf{j}}{}^{\boldsymbol{\Sigma}} + \widehat{\mathbf{C}}_{\mathbf{i}}\mathbf{v}_{\mathbf{m},\mathbf{i}} + \widehat{\mathbf{G}}_{\mathbf{i}} \tag{8}$$

where $\mathbf{C_{ff}}$ is as in Equation (2). In addition to direct position regulation, the publication also shows the use of position control within admittance control.

In addition to the clarified control strategies, the force control as a system of active flexible fixtures is analysed for stability purposes. Thus, an assembly contact model without energy terms is proposed for exemplary purposes. Two different assembly scenarios using different control strategies are subsequently analysed, by using a system state matrix to establish stability statements for the use of multiple flexible fixtures in multi-workpiece scenarios. The results of the stability analysis relating to different force control strategies are summarised as follows:

- *Direct force control*: when a single flexible fixture is actively controlled, the control system is stable for all positive gains. When multiple fixtures are in direct force control, anchoring or an additional virtual potential field is necessary.
- *Indirect force control:* when a single flexible fixture is actively controlled, the control system is stable for all positive gains. When several flexible fixtures are in indirect force control and driven by an external stimulus, the contact force resulting from the actions of each flexible fixture under indirect force must be linearised.

Since this publication integrates Publication E into position control and delivers a standardised control strategy for active flexible fixtures, the answer to *RQ* 3 is realised. Thus, the prescriptive study initiated by Publication D for a new impact model is complete. Thus, the Prescriptive

Stage of the DRM is finalised by this publication. Like Publications D and E, this publication also conducts an experiment to produce an internal evaluation of the Descriptive Study II stage.

Conclusions

This publication concludes that fundamental manipulator dynamics and control strategies can be adapted to flexible fixturing scenarios, since flexibility in reconfigurable fixtures is achieved by kinematic structures. This remains consistent with the conclusions of Publication D. Moreover, as long as stability statements are fulfilled, the performance of the flexible fixtures can be determined by tuning the control parameters. Thus, the active control of flexible fixtures can be summarised as force and position control in respect of errors in the process parameters. Due to its generic second-order behaviour of admittance force control, different roles (depending on the process type) can also be used to facilitate various process demands.

4.8 PUBLICATION G

n-PRPR: Kinematics Analysis of a Novel Translational Parallel Kinematics Machine

I. Erdem, H. Abadikhah, "n-PRPR: Kinematics Analysis of a Novel Translational Parallel Kinematics Machine", *Robotics and Computer-Integrated Manufacturing*, 2019. (To be submitted)

Description

Similar to Publications A, B and C, Publication G is also project-driven and aims to contribute to the design procedure proposed in Publication D. The publication executes the analysis steps given in Publication D and exemplifies their utilisation within the procedure. The publication also aims to show that the efficiency of flexible fixtures can be readily facilitated when an appropriate kinematic structure is available. Furthermore, the publication adds to the general body of knowledge in robotics and describes the mechanical advantages of using the proposed kinematics structure as a flexible fixture.

Thus, the publication contributes to this thesis by conducting a descriptive study, demonstrating the new impact model's applicability. The publication also conducts experiments for internal evaluation. This means it is incorporated into the Descriptive Study II stage of the DRM.

Aim

The aim of this publication is to present the kinematics and Jacobian, stiffness and workspace analyses of an N-PRPR parallel kinematics machine.

Experiments/prototype

The publication uses each analysis section for 3-PRPR and 4-PRPR mechanisms and shows a prototype 3-PRPR robot, developed to demonstrate the proposed mechanism.

Results

The results presented in this publication aim to offer an answer *RQ* 2 by demonstrating the applicability of the design procedure in Publication D, in respect of fundamental flexible fixture efficiency criteria. The publication also shows the efficiency increase for flexible fixtures, when fundamental efficiency criteria are satisfied.

- *Mechanism analysis*

The publication analyses the mechanism's PR$\underline{\text{P}}$R-limb (Prismatic-Revolute-Prismatic-Revolute) to demonstrate that the proposed PKM is translational. The analysis starts by building a transformation matrix from a base coordinate frame [**O**] to the end-effector [**E**] of a limb located at β_n degrees about Z_O-axis in an n-polygon. β_n describes the rotation about Z_O-axis that aligns as X_O-axis to the axis of rotation ($X_{n,2}$) for the first revolute joint. The transformation is then continued with the rotation of the first prismatic joint by $\alpha_{n,2}$ around $X_{n,2}$. Then, the length of the actuated prismatic ($\mathbf{d}_{n,3}$) joint is translated on the $Z_{\mathbf{n,3}}$ axis that is perpendicular to $X_{\mathbf{n,2}}$ and $Y_{\mathbf{n,3}}$ -axes. The transformation is finalized with a rotation about the axis of rotation for the last revolute joint by $\alpha_{n,2}$ around $X_{\mathbf{n,4}}$.

So, each transformation matrix's rotation vector sets are equated with each other as they share a common end-effector. The results of the analysis show that the sum of angular joint values ($\alpha_{n,2} + \alpha_{n,4}$) for each limb must be 0. Consequently, the rotational part of the transformation matrices for each limb must be an identity matrix. This proves that the proposed mechanism is rotation-free. By analysing the translational vector (**P**) of the transformation matrix, the publication finds that the components of the translational vector can move independently in the x, y and z axes in [**O**].

- *Kinematics analysis*

The publication presents the forward and inverse kinematics of a general n-PRPR mechanism, along with its application in 3-PRPR and 4-PRPR PKMs. Thus, inverse kinematics for an n-PRPR with β_1=0 become:

$$\begin{gathered} \|\mathbf{d}_{1,3}\| = \sqrt{\left(\mathrm{P_y} + (\mathrm{r'} - \mathrm{r})\right)^2 + \mathrm{P_z}^2} \\ \|\mathbf{d}_{n,3}\| = \sqrt{\left(-\mathrm{s}\,\beta_n \mathrm{P_x} + \mathrm{c}\,\beta_n \mathrm{P_y} + (\mathrm{r'} - \mathrm{r})\right)^2 + \mathrm{P_z}^2}. \end{gathered} \tag{9}$$

By applying Equation (9), the following equations for 3-PRPR are determined:

$$\begin{gathered} \|\mathbf{d}_{1,3}\| = \sqrt{\left(\mathrm{P_y} + (\mathrm{r'} - \mathrm{r})\right)^2 + \mathrm{P_z}^2} \\ \|\mathbf{d}_{2,3}\| = \sqrt{\left(-\mathrm{s}(2\pi/3)\mathrm{P_x} + \mathrm{c}(2\pi/3)\mathrm{P_y} + (\mathrm{r'} - \mathrm{r})\right)^2 + \mathrm{P_z}^2} \\ \|\mathbf{d}_{3,3}\| = \sqrt{\left(-\mathrm{s}(4\pi/3)\mathrm{P_x} + \mathrm{c}(4\pi/3)\mathrm{P_y} + (\mathrm{r'} - \mathrm{r})\right)^2 + \mathrm{P_z}^2}. \end{gathered} \tag{10}$$

Similarly, the equations for 4-PRPR are:

$$\begin{gathered} \|\mathbf{d}_{1,3}\| = \sqrt{\left(\mathrm{P_y} + (\mathrm{r'} - \mathrm{r})\right)^2 + \mathrm{P_z}^2} \\ \|\mathbf{d}_{2,3}\| = \sqrt{\left(-\mathrm{P_x} + (\mathrm{r'} - \mathrm{r})\right)^2 + \mathrm{P_z}^2} \\ \|\mathbf{d}_{3,3}\| = \sqrt{\left(-\mathrm{P_y} + (\mathrm{r'} - \mathrm{r})\right)^2 + \mathrm{P_z}^2} \\ \|\mathbf{d}_{4,3}\| = \sqrt{\left(\mathrm{P_x} + (\mathrm{r'} - \mathrm{r})\right)^2 + \mathrm{P_z}^2}. \end{gathered} \tag{11}$$

Based on Equation (9), the forward kinematics of the n-PRPR (again for β_1=0) becomes:

$$\begin{gathered} \left(\|\mathbf{d}_{1,3}\|\right)^2 = \mathrm{d}_{1,3}{}^2 = \left(\mathrm{P_y} + (\mathrm{r'} - \mathrm{r})\right)^2 + \mathrm{P_z}^2 \\ \left(\|\mathbf{d}_{n,3}\|\right)^2 = \mathrm{d}_{n,3}{}^2 = \left(-\mathrm{s}\,\beta_n \mathrm{P_x} + \mathrm{c}\,\beta_n \mathrm{P_y} + (\mathrm{r'} - \mathrm{r})\right)^2 + \mathrm{P_z}^2. \end{gathered} \tag{12}$$

By analysing Equation (12), the publication finds that any β_n other than $k\pi/2$ ($k \epsilon Z$) (the solution to the forward kinematics) will yield a 4^{th}-degree polynomial. As with inverse kinematics, the publication applies Equation (12) to 3-PRPR and 4-PRPR mechanisms, to demonstrate the resulting forward kinematics equations.

- *Jacobian analysis*

By taking the time derivative of Equation (9) and rearranging the derived equations, a general velocity mapping equation is realised as follows:

$$\dot{d}_{n,3} = s\beta_n c\alpha_{n,2} V_x + c\beta_n c\alpha_{n,2} V_y + s\alpha_{n,2} V_z. \qquad (13)$$

Using the preceding equation, the publication demonstrates the forming of Jacobian matrices based on the angular distribution of the limbs. Similarly, the publication shows Jacobian matrices for both 3-PRPR and 4-PRPR mechanisms.

- *Workspace analysis*

A parametric workspace analysis is conducted in this publication to demonstrate the capacity of the proposed mechanism's workspace to be determined in both conceptual and detailed fashion. Due to its parametric nature, the proposed PKM's capability to evaluate its workspace allows it to be modified conceptually in respect of reach requirements, regardless of the type of process. The parametric workspace is initially divided into two volumes, namely feasible workspace (V_f) and limited workspace (V_k). The proposed mechanism's reachability is more feasible in terms of operational capability in V_f than for limited volumes (V_k) due to the end-effector's workspace converging to the maximum and minimum points. The feasible workspace of the mechanism is bound to the shape of the baseplate, as the volume is to the dimensions of prismatic joints (maximum and minimum lengths) and base-plate area. The limited volumes are defined by an arc, the radius of which is the maximum length of the actuated prismatic joint.

- *Stiffness (rigidity) analysis*

A parametric stiffness model is presented to support the stiffness analysis of the proposed mechanism, based on the Jacobian. The publication demonstrates the stiffness mapping in respect of the workspace generated and the load-bearing capacity of the PKM, based on the architectural capacity. This feature allows the PKM to be evaluated conceptually for its suitability to various processes. Moreover, an FEA can be conducted to finalise a detailed design. Thus, the publication offers a workspace-based stiffness model with an algorithmic stiffness mapping. The algorithm uses $\mathbf{F} = k\,\mathbf{J}^{\mathbf{T}}\mathbf{J}\,\Delta\mathbf{x}$ with $\mathbf{F} = [0\ 1\ 1]^{\mathbf{T}}$ N to compute the length of deflection $\Delta\mathbf{x}$ over the workspace. Accordingly, it is suggested that the forces be scaled to compute deflection linearly.

Conclusions

This publication concludes on the proposed PKM, relating to how an appropriate kinematic structure can support the use of PKMs in demanding industrial processes. As part of such demanding processes, fixturing may also benefit readily. Having a relatively simple kinematic structure, the mathematical ease of analysis of the proposed PKM may support various design procedures.

V

DISCUSSION

This chapter aims to provide answers to the research questions of this thesis and discuss their integration into the frame of reference. The chapter will also evaluate the research approach and verification and validity of the results. There is also a presentation of possible future work in which this thesis might be used.

5.1 ANSWERS TO RESEARCH QUESTIONS

This section will provide the answers to the research questions, based on the results given by the publications presented in Chapter 4. Moreover, the answers will be evaluated in respect of their integration into the frame of reference and research gaps given in Chapter 2.

5.1.1 RESEARCH QUESTION 1

What are the criteria that can be used to describe the efficiency of flexible fixtures?

In the search for a description of flexible fixture efficiency, the publications in this thesis used terminology relating to fundamental fixture criteria, production system parameters, flexible fixture efficiency criteria and metrics. As this section aims to take a position on integrating the publications' results, this thesis proposes to merge the overlapping criteria under the production system's performance parameters. At the same time, the fundamental and flexible fixture criteria identified in the publications are hierarchically distributed and classified as sub-criteria. To support the transition to the metrics of *RQ* 2, each sub-criterion is complemented with a statement describing the anticipated state.

In respect of the fundamental efficiency of fixtures, the criteria presented in Publications A, B, C and D as weight, stiffness, accuracy and repeatability are evaluated for the first criterion (C1). As stiffness, accuracy and repeatability of a specific flexible fixture evaluate its capacity in respect of a set of differing processes, the first criterion is left with weight and dimensions (which describe the physical aspects of a flexible fixture). Thus, the first criterion is reduced to aspects enabling a flexible fixture to be evaluated directly according to its physical properties (which are independent of its remaining criteria). In addition to decoupling fundamental aspects from the remaining criteria, this approach simplifies the evaluation procedure. Hence, a neutral statement for C1 is formulated as follows: the weight and minimum size of a flexible fixture influence flexible fixture efficiency. The sub-criteria are essentially described by weight and size respectively; as the total weight and minimum fundamental dimensions of a flexible fixture. Furthermore, the anticipated states for each sub-criterion can be defined according to a limit set by the target process and production system (Publication D). Since an increase in weight and size negatively impacts flexible fixture efficiency, an anticipated state for each sub-criterion can be formulated as follows: the efficiency of a flexible fixture increases when it is designed lighter and smaller in respect of production system requirements.

The second criterion (C2) represents the efficiency relating to flexibility. In Publications A, B, C and D, flexibility is discussed from a physical capability perspective. By remaining consistent with the preceding status, the results of this thesis also describe flexibility as the physical capability of a fixture to be used for multiple workpieces and processes within multiple production systems. As the production system requirements are translated into meta-performance of flexible fixtures, a neutral statement concerning C2 can be made as follows: a flexible fixture's efficiency is influenced by its capability to satisfy the requirements of a given set of workpieces and processes. The sub-criteria relating to C2 can be handled according to the descriptions provided in Publication D, in terms of reconfigurability, reusability and modularity. Specifically, the reconfigurability sub-criterion focuses on workpiece fulfilment, with C2 translated as the capability of a flexible fixture to locate and secure multiple workpieces without requiring any rebuilding. Similarly, the reusability sub-criterion is translated into C2, as the capability of a flexible fixture to withstand process-related requirements (namely, its capability to withstand forces within an acceptable deformation range and to locate a workpiece within the limits of accuracy and repeatability). Thus, the omitted fundamental fixture criteria are re-used to specify the suitability of a flexible fixture to a given set of differing processes. The above sub-criteria of C2 establish the relevant flexibility efficiency when a flexible fixture is positioned locally at a specific position, with its existing internal equipment. However, a flexible fixture's components may be exchanged to extend its physical capability. In searching for exchange capability, Publication C uses the terms "scalability & standardisation", whereas Publication D generalises these terms under "modularity". Hence, the modularity sub-criterion proposes the last aspect of C2, as the capability of a flexible fixture to be rebuilt for different workpieces and processes using standardised components. It is important to note that the difference between modularity and reconfigurability resembles the difference between modular and reconfigurable fixtures. An illustration of this difference in flexible fixture efficiency may be formulated, if time is introduced into the equation. In contemplating reconfigurability, a fixture designer considers a range of available workpieces. Investigating modularity means considering the capability of a flexible fixture to be transformed for workpiece and process targets beyond the scope of current applications. Given the above information, the anticipated states of each sub-criterion can also be stated. Thus, the anticipated states for reconfigurability, reusability and modularity can be formulated as follows: a flexible fixture's efficiency is proportional to the number of fulfilled workpieces and processes and used standard components.

The third criterion (C3) focuses on the cost-effectiveness of flexible fixtures, where the cost of a flexible fixture is described as the total capital and setup costs (Publication D). As with previous criteria, a neutral statement regarding C3 can be articulated as follows: a flexible fixture's cost has an impact on the efficiency of flexible fixtures. Inherently, the sub-criteria describing C3 can be classified as the investment and setup costs. The investment cost of a flexible fixture describes the cost of equipment used directly in the flexible fixture. The setup cost, on the other hand, describes the auxiliary technologies or equipment needed to set up and prepare the flexible fixture for operation. To illustrate the difference in setup cost, one could look at a laser tracker needed to set up a group of flexible fixtures. Thus, the cost of a laser tracker is divided per flexible fixture unit and registered to the setup cost under the relevant sub-criterion. The anticipated states are based on the minimised cost, the formulation of which may be articulated as follows: increased investment and setup costs nearing or exceeding a dedicated limit from the target production system reduce the efficiency of a flexible fixture.

The fourth criterion (C4) describes the time aspect of flexible fixtures. As with the setup cost of C3, this criterion also elaborates on the impact of auxiliary activities needed to setup the flexible fixture (Publications A, B, C and D). Hence, a neutral statement describing C4 can be given as follows: the time required to set up a flexible fixture affects the efficiency of flexible fixtures. Since C4 relates only to setup activities, the sub-criterion is immediately given as setup time. Since setup time minimisation is sought for all types of fixtures, the anticipated state for this sub-criterion is stated as follows: increasing the amount of time required to setup a flexible fixture affects flexible fixture efficiency negatively.

The fifth and final criterion (C5) describes the efficiency of flexible fixtures from a quality perspective. The quality of flexible fixture efficiency is defined as the process robustness realised by the flexible fixture, with this realisation correlated to use of flexible fixtures in an operation (Publications D and F). Hence, the neutral statement regarding C5 is formulated as follows: a flexible fixture's capability to realise process robustness influences the flexible fixture efficiency. Moreover, Publication D classifies C5 under the sub-criteria of diagnosability, reliability and convertibility. For diagnosability, Publication D describes process as the capability of a flexible fixture to exchange process-related information. Publication F extends the initial description by Publication D and finalises the description of diagnosability as the capability of a flexibility fixture to exchange and regulate process-related parameters. Thus, the anticipated state of this sub-criterion can be stated as follows: flexible fixture efficiency increases as flexible fixtures exchange and regulate process parameters. The second sub-criterion, reliability, tackles the notion of quality in the light of the body of flexible fixtures. Specifically, the less error-prone the standard components in a flexible fixture are, the more disposed flexible fixtures are to maintain process robustness. The third sub-criterion, convertibility, describes the capacity of a flexible fixture to be complemented by other technologies and thus realise various tasks. This sub-criterion emphasises the importance of flexible fixtures cooperating with other production technologies and showing capacity to conduct tasks beyond fixturing, such as assembly (in Publications B, C and D). Thus, it is considered positive in terms of efficiency if a flexible fixture can be converted in order to realise various operations.

In conclusion, the efficiency of a flexible fixture is described from a multi-dimensional perspective. The answer to *RQ* 1 shows that evaluating a flexible fixture requires consideration of all the lengths within this multi-dimensional setting. Stating sub-criteria and their relevant anticipated states allows multi-dimensional aspects of flexible fixtures to be determined and described and provides relevant background for *RQ* 2. The summary of the answer to *RQ* 1 is given in Table 4.

Table 4. Criteria for flexible fixture efficiency, with their sub-criteria and anticipated states.

<table>
<tr><th>No</th><th>Criteria</th><th>Sub-criteria</th><th>Anticipated state for flexible fixture efficiency</th></tr>
<tr><td rowspan="2">C1</td><td rowspan="2">Fundamental</td><td>Weight</td><td>Increase in weight affects efficiency negatively</td></tr>
<tr><td>Size</td><td>Increase in size affects efficiency negatively</td></tr>
<tr><td rowspan="3">C2</td><td rowspan="3">Flexibility</td><td>Reconfigurability</td><td>Increase in number of satisfactory workpieces affects efficiency positively</td></tr>
<tr><td>Reusability</td><td>Increase in number of satisfactory processes affects efficiency positively</td></tr>
<tr><td>Modularity</td><td>Increase in number of standard components affects efficiency positively</td></tr>
<tr><td rowspan="2">C3</td><td rowspan="2">Cost</td><td>Investment cost</td><td>Increase in investment cost affects efficiency negatively</td></tr>
<tr><td>Setup cost</td><td>Increase in setup cost affects efficiency negatively</td></tr>
<tr><td>C4</td><td>Time</td><td>Setup time</td><td>Increase in setup time affects efficiency negatively</td></tr>
<tr><td rowspan="3">C5</td><td rowspan="3">Quality</td><td>Diagnosability</td><td>Flexible fixture efficiency increases as flexible fixtures exchange and regulate process parameters.</td></tr>
<tr><td>Reliability</td><td>Increase in standard component reliability positively affects efficiency.</td></tr>
<tr><td>Convertibility</td><td>Efficiency increased by capacity to be complemented with external technologies and realise various tasks using flexible fixtures.</td></tr>
</table>

5.1.2 RESEARCH QUESTION 2

How can these criteria be methodically used in the design of flexible fixtures?

The efficiency criteria described in previous sections show that the notion of efficiency needs to be measured relative to production system requirements. This, accordingly, leads to a transition of the anticipated states given in Table 4 into usable metrics. Publication D presents such conversion and the relevant metrics are proposed for use in a design procedure (see Table 3). Naturally, the proposed metrics may be modified, improved or reinterpreted. However, their construction relies on the fundamental rationale that a flexible fixture's efficiency is not universal such that a flexible fixture can be used in every production system with the same efficiency. Thus, a certain level of customisation is needed to adapt a flexible fixture to a target production system. However, as demonstrated by Publications A, B, D and G, there are various kinematical forms (regardless of kinematic classification) upon which the design of flexible fixtures can be designed. Therefore, an efficiency-oriented design of a flexible fixture needs to be conducted comparatively where multiple possible solutions are evaluated simultaneously for the target production system (Publication D). In addition to comparing multiple flexible fixtures, the comparison of multiple production systems for a flexible fixture can also be achieved. By allocating weights to the efficiency metrics and applying a weighted-average, a final efficiency value can be realised for each flexible fixture, in respect of different production system characteristics (Publication D).

Before initiating a design procedure, it is important to take an abstract stance on the metrics and their impact on that design procedure. It is clear from the proposed efficiency scheme that, for an efficient flexible fixture design, a designer is expected to have knowledge of two distinct aspects. The first is that a designer needs access to a "library of knowledge" on the components of multiple flexible fixtures. The reason for this constraint is to enable the customisation process in a standardized manner so that the adaptation and comparison processes can be conducted synchronously for a target production system. The second aspect is that the designer is expected to have studied the target production system with respect to the criteria metrics. Consequently, by formulating the efficiency weights, it is ensured that the design procedure revolves around the notion of customised flexibility, rather than having a universal flexible fixture that is claimed to work for all production systems.

With the integration of efficiency by means of metrics and determination of knowledge prerequisites, an overall approach to design procedure can be formulated. Publications B, C and D demonstrate that, a design procedure should enable decision-making before the detailed design is initiated where the decision-making is based on the comparative efficiency evaluation in a conceptual design stage. The fundamental reason behind instigating the conceptual stage is to eliminate the need for a detailed design of each solution in order to make a choice. This way, the amount of time needed during flexible fixture design to refine a possible solution can be drastically reduced. With the conceptual stage instigated after knowledge prerequisites are fulfilled, a kinematic structure need to be determined; this establishes the backbone of the prospective flexible fixture. Based on the kinematic structure, five distinct consecutive decisions are necessitated. Firstly, the actuation type must be determined based on two alternatives; internal and external. Secondly, the method by which the prospective flexible fixture will maintain its position is determined on an abstract level, in respect of the type of power source needed. Thirdly, mechanical components are chosen in respect of custom or standard. Fourthly, control system components are determined with respect to two identified options, whether flexible fixtures will share a controller or have individual control systems. Finally, the controller software capabilities are determined in respect of standard and customised functionalities, such as robotics and active control, respectively. For active control, the possible strategies are either position control or force control, with force control further elaborated upon by direct or indirect control strategies (see Section 5.1.3). In the last decision, the functionalities should be identified in sufficient detail to facilitate the cost calculation (an example of which may be seen in Publication D's experiment). As the conceptual design stage is completed and relevant decisions made, candidate flexible fixtures are comparatively evaluated using the equations in Table 3 for the conceptual analysis and verification stages. Thus, a prospective flexible fixture is chosen and transitioned into the detailed design and analysis stage.

With the flexible fixture's conceptual features determined, the detailed design requires three distinct steps to complete a flexible feature for final verification. The first step involves detailed design and assembly of both mechanical and control system components. Following assembly, the second step (detailed analysis) is initiated. Since the flexible fixture is classified kinematically, it is anticipated that the analysis of a flexible fixture will be conducted based on kinematics, dynamics, singularity and stiffness. The final step involves detailed design of controller software. It is important to note that the results of the previous analysis step are incorporated into the flexible fixture in the last step, along with the software functionalities determined in the conceptual design stage. With the finalisation of the detailed design stage, the verification stage (identical to conceptual analysis and verification) is repeated to determine the final efficiency values.

In both conceptual and detail verification stages, the evaluation is conducted based on feedback mechanisms. A feedback mechanism for conceptual verification may occur in major dimensions including change of kinematic structure, whereas the detailed verification focuses on detailed design modifications to established conceptual features. In addition to major changes, both verification stages enable customisation of an individual flexible fixture. This allows comparison to its former self, which is based on the same library of knowledge. Hence, a certain level of efficiency is ensured throughout the design procedure. It is important to note that certain design choices and modifications do not necessarily affect each metric positively where in some cases trade-offs can be observed (as shown in Publication A). Therefore, the conceptual design and analysis stage must be used comprehensively so as to capture these trade-offs by analysing the impact of design customisation, particularly when distributed across the production system weightings.

In addition to the metrics' interaction with each other in respect of overall production system weightings, the measurement of each metric within the design procedure is a key aspect, particularly on a conceptual level. Regarding Publication D's insight into the measurement of reconfigurability and reusability in conceptual verification, the correlation of physical workpiece and process parameters to design data requires meta-knowledge about workspace, stiffness and accuracy/repeatability. This meta-knowledge can be approached from two possible perspectives. Firstly, general estimation models can be used for workspace, accuracy and repeatability, as shown in Publication D. Secondly, parametric conceptual models can be developed, as demonstrated by Publication G. Publication G shows that a conceptual Cartesian stiffness model based on Jacobian matrix and appropriate limb stiffness can be used directly for the reusability metric, due to the availability of an appropriate kinematic structure. Moreover, a parametric workspace model can be readily used for conceptual workspace computation, to determine the reconfigurability of a kinematic structure. The availability of such parametric models via an enabling kinematic structure facilitates a more accurate evaluation stage – which eventually contributes to the efficiency of flexible fixtures.

5.1.3 RESEARCH QUESTION 3

How can flexible fixtures be actively controlled to increase their efficiency?

The answers to *RQ* 1 and *RQ* 2 present the connections of flexible fixtures to active control, with C5's diagnosability sub-criterion (in relation to customised controller software) attainable via active control of flexible fixtures to realise process robustness. The fundamental notion of introducing the active control concept into flexible fixtures is based on the reasoning that flexible fixtures share reconfigurable elements that active fixtures inherently have (Publications B and C). Thus, using the potential for process robustness via flexible fixtures is part of C5's diagnosability. Furthermore, active control schemes require consideration in both the conceptual and detailed design stages of flexible fixtures, as demonstrated in the answer to *RQ* 2. This eventually leads to the need for a standardised model that can support flexible fixture design (Publication D).

Before describing the active control of flexible fixtures by using internal actuation, it is important to explain that the notion of process regulation can be realised externally by other production technologies. However, when active control is sought by using external technologies, the mathematical decision mechanism of active control occurs outside the flexible fixture, regardless of whether the flexible fixture collects and shares information about the workpiece or process (Publications A and C). Should external active control mechanisms be chosen, the line describing whether a flexible fixture contributes to process robustness is not clearly expressed. Such a case may be deduced from Publication A, in which the process corrections are accredited to a case-based reasoning system, even though modifications to the flexible fixture are conducted. Therefore, a condition statement forming the first part of the answer to *RQ* 3 can be formulated as follows: in order for a flexible fixture to increase its efficiency via active control, the prospective flexible fixture must have internal actuation structure to analyse and regulate the condition, independently of external technologies. It is important to complement the preceding condition by stating that a sensor added to a flexible fixture for active control is exempt, since adding a sensor is part of the flexible fixture and should be reflected onto other metrics such as investment cost.

Fundamentally, the objective of active control is identical regardless of what physical form the fixture may have. Thus, the process regulation via position and force control schemes also constructs two aspects of activeness in flexible fixtures. On the other hand, flexible fixtures show variance in form of their kinematics, with multiple chains of kinematics structures requiring in-depth control schemes. This difference in flexible fixtures shifts the focus of general active control schemes from being workpiece-oriented (where the workpiece designs the fixture rather than the other way round) to being fixture-oriented. Naturally, this remains alongside the fundamental philosophy of flexibility, in which an actively controlled, flexible fixture is expected to work regardless of the workpiece geometry or process dynamics. Thus, maintaining a relatively universal state via workpiece- oriented active control remains insufficient in this endeavour.

Publication F shows such a transition, from a workpiece-oriented active control scheme to fixture-oriented development. The first aspect of fixture-oriented development is that the flexible fixture is described using standard manipulator dynamics. This requires that a flexible fixture is expected to have a kinematic description. By following this description stated in *RQ* 2, manipulator dynamics (the output of the design procedure) can be readily integrated into the active control scheme. With the dynamics of the flexible fixture established, the active control of flexible fixtures can be transitioned into Cartesian space to establish a “common language” whereby a model of a flexible fixture system can be developed. The system modelling of a flexible fixture includes the dynamics of workpiece, process and other fixtures, as shown by Publication F in Figure 18. By incorporating the properties of each workpiece into their relevant flexible fixture in state-space formulation, the system model can be readily derived for the contact forces and a control command issued accordingly (see Equations (3) and (4)). Consequently, the proposed model can be prepared for position and force control strategies, regardless of flexible fixture’s kinematic form or workpiece.

For position control of flexible fixtures, a control strategy can be formulated, based on the notion of regulating the position of a flexible fixture’s end-effector. As disturbances to the positional robustness may manifest in oscillatory form, pure feedback or repetitive controllers remain insufficient for providing the appropriate performance in tracking the oscillatory disturbance signal, unless there is preliminary knowledge of the fundamental content of the disturbance. Similarly, feedforward control methods using a pure process inverse to track signals also require that process being very closely identified and not suffering from stability problems. Based on the pitfalls of existing control schemes, a new controller is proposed by this thesis based on the Hilbert transform (Publication E). By using the proposed controller, any linear stable process can be forced to track any disturbance signal, whether multi-component, frequency or amplitude-modulated (see Equation (2)). Moreover, by integrating into a feedback control system, non-periodic signals can also be regulated. Since a flexible fixture is also a kinematic device described by manipulator dynamics, this controller can be integrated into the control command of a flexible fixture in an active control scheme (see Publication F’s Equation (8)). Consequently, any flexible fixture can be utilised to regulate the position of an end-effector to process nominals, regardless of the nature of the disturbance.

Active force control of flexible fixtures can be realised by using two distinct methods. Using a direct force control scheme (see Publication F’s Equation (5)), a flexible fixture can gain the capability to regulate the sum of contact forces occurring on a workpiece. Using the direct force control strategies, a single flexible fixture can be utilised for various purposes in assembly, such as automated assembly or ensuring contact during a disturbance. In addition, the end-effector of a flexible fixture can also be used to regulate the fixture’s contact force with a workpiece under process forces, as in machining. The second control strategy for a flexible fixture is to use an indirect approach to force control. Stemming from admittance control principle, a flexible fixture can gain the capability to exhibit compliance (see Publication F’s Equations (6)-(7)). Through this compliance, a workpiece can be actively controlled so as to exhibit the behaviour of a mass-spring-damper, the parameters of which can be specified with respect to different process requirements. Moreover, the notion of compliance can be directly correlated to force errors, generated either by an external stimulus such as a drilling tool or via contact forces. By using the proposed control strategies, different types of roles can be appointed to any flexible fixture, thus negating the force disturbances occurring in processes.

The above force control strategies for active control of flexible fixtures describe the individual capabilities of a single flexible fixture. Naturally, some applications require the interaction of multiple workpieces manipulated by different flexible fixtures (as in Publication C). When a system of active flexible fixtures interact with each other via workpieces, the stability of a system must be ensured. Even though such a system may be designed in many forms, certain stability rules can be appointed for each force control strategy (Publication F). Specifically, anchoring or an additional virtual potential field is necessary when multiple fixtures are in direct force control. In an indirect force control system, the contact force resulting from the actions of each flexible fixture under indirect force must be linearised, with linearisation requiring estimation of stiffness at contact locations. It is important to note that when flexible fixtures interact with non-rigid workpieces, the stiffness of the workpiece must also be considered so as to realise greater accuracy in process quality.

In conclusion, active control for flexible fixtures can be realised by using position and force-control strategies. By setting the objective of each control strategy as the regulation of the process nominals, flexible fixtures will aim to contribute to the quality of their applied process. Eventually, this leads to an increase in their efficiency. Although the reflection of active control in the diagnosability metric is specified as binary, this thesis encourages flexible fixture designers to develop more advanced metrics in respect of the existing fixture system.

5.1.4 RELATING TO FRAME OF REFERENCE

The frame of reference for fixture efficiency presented in Section 2.2 highlights the fact that the search for efficiency in flexible fixtures is presented in conjunction with production system characteristics. The state-of-the-art for fixture efficiency treats the fixture as an “extension” to the workpiece and process, with the fixture’s efficiency evaluated per workpiece and process. The answer to *RQ* 1 shows that such a state does not function for flexible fixtures as per-workpiece and process is not compatible with the notion of flexibility. Hence, a set of criteria plus metrics is determined for flexible fixture bodies. Naturally, these metrics overlap with certain state-of-the-art criteria. Regarding the stiffness requirements for fixtures, the workpiece deformation is decoupled. However, the stiffness analysis of a flexible fixture body is proposed as a construct, which can be deduced from a general stiffness statement into target process forces. Similarly, tolerance requirements are reinterpreted into the motion aspect of flexible fixtures. This complements the accuracy and repeatability analysis of locators. The accessibility requirements for the state-of-the-art are directly decoupled from flexible fixtures, as it is shown that accessibility correlates to layout design. However, it is important to note that flexible fixtures require use in accordance with a designed layout. This interaction between layout and flexible fixtures can be realised by allocating the dimensional restrictions to the efficiency metric “dimensions”. The operability requirements are only reflected in the form of flexible fixture weight. However, the concept of ease-of-use is intentionally omitted in respect of the delimitations of Section 1.3. In the state-of-the-art for cost and time metrics, the determined research gap is occupied by relevant metrics defined as the investment cost and setup cost and time. It is important to note that several researchers point out the importance of design time, this is not presented as part of the efficiency metrics. The fundamental reason behind the exclusion of design and delivery time metrics is that measuring the time to finish a design and deploy the proposed design procedure is unique to the designer’s capacity and network of suppliers.

The answer to *RQ* 2 occupies the body design step for reconfigurable fixtures within the fundamentals of fixture design given in Section 2.3. Thus, the proposed design procedure remains consistent with the remaining steps, since it describes a single flexible fixture body according to given criteria. As the design procedure uses the output of a layout design in a predetermined setup (or setups), the relevant workpiece, process and dimensional restrictions are inherently embedded. Another possibility for interacting with state-of-the-art fixture design might also require modification of the layout according to the design procedure’s output.

The established body of knowledge regarding active control of flexible fixtures aims to address the presented research gap given in Section 2.5. In the state-of-the-art analysis for active fixture control, it is shown that the existing body of knowledge relies on the control of rather simplistic elements, customised according to a single workpiece and process. Thus, a generalised control scheme concerning advanced flexible fixtures is assessed as the research gap. The answer to

RQ 3 occupies the preceding gap by introducing manipulator dynamics. Using the standard dynamics approach, it aims to ensure that any established control strategy remains compatible with flexible fixtures that can be classified with a kinematics structure. A transition from workpiece-oriented to fixture-oriented development is thus provided. Based on the manipulator dynamics approach, general workpiece dynamics is incorporated using Cartesian space formulation along with various force control strategies. In the state-of-the-art, it is shown that the active control strategies are classified as position control, force control and chatter suppression. The control strategies proposed by this thesis consider only position and force control strategies. However, by introducing indirect force control strategy, chatter suppression can also be realised by any flexible fixture. The use of active control strategies for flexible fixtures is also expanded via system and stability analyses. This enables flexible fixtures to be used in processes requiring more than a single workpiece (as in assembly). Thus, the state-of-the-art's limitation on active fixturing in machining processes is exceeded.

5.2 EVALUATING THE RESEARCH APPROACH

This thesis used knowledge of design research to guide its scientific efforts to realise its aim. This is illustrated in Section 3.4.1, which states that certain adaptations and interpretations (from the context of design research into fixture development) are necessary to achieve an aim that encompasses multi-dimensional research, as shown in Sections 2.5 and 3.2. It is the understanding of this thesis that this multi-dimensional setting is not unique to flexible fixtures and that other production technologies are influenced by changes in paradigms, such as the newly emerging cyber-physical production systems. From that particular point of view, it is clear that design research methodology (DRM) offers advantages in developing models that incorporate relevant dimensions and thus prove effective. However, DRM is very restricted in the outcomes of each of its stages. Thus, interpreting the outcome into new domains other than design research is considered risky, as it may lead the research astray. To avoid a risky path of technological development (examining more than one specific technology for a specific process), this thesis encourages a formal research methodology specifically developed for production technologies. Moreover, a natural question arises regarding external evaluation (which is not considered in this thesis). The application of the results of this thesis in an industrial setting is inherently beneficial to further development of the research topic. While such endeavour is beneficial and encouraged, applying a technology to a production system requires activities beyond the scientific aim of this thesis. Therefore, the latest stage of DRM requires special formulation in its adaptation.

5.3 EVALUATING THE RESULTS

In relation to the definitions of verification and validity given in Section 3.5, the results achieved via this thesis' publications will be discussed. Accordingly, the verification aspect will be presented first. Statements will be presented later, which describe the validity of this thesis.

5.3.1 VERIFICATION

Regarding the experimental nature of each publication, the falsifiability aspect of each theory-driven publication is supported by transparent experimental procedure. The falsifiability of project-driven publications remains more ambiguous compared to theory-driven publications. However, by evaluating these publications through verification elements, any threats to verification of the results will be analysed. Thus, based on the definitions of Buur [170], the verification analysis is as follows:

- *Consistency*: the results of each publication are iterative in nature. This remains consistent within the body of knowledge, as the results enable subsequent knowledge generation.
- *Coherence*: the results of each publication are consistent with the teachings of the theory and general state-of-the-art used. Moreover, the anticipated results of the chosen methodology remain in harmony with the abstract state of the publications.
- *Completeness*: as the relationship to the state-of-the-art demonstrates, the reduction of the presented results can be applied to a vast range of fixtures. Moreover, a generalised body-of-knowledge is sought by the theory-driven publications, to expand the applicability of the body of knowledge presented in this thesis.
- *Ability to explain unique phenomena*: each publication stems from a unique phenomenon connected to an industrial need via a project. Since such connection is preserved by demonstrators and experiments, the body of knowledge is integrated with explanatory capabilities.

External verification in this thesis is limited to experiments and expert verification of the demonstrators. Furthermore, each publication is peer-reviewed and project-driven publications compare their results to the requirements of their individual projects.

5.3.2 VALIDITY

The findings of this thesis are evaluated from statistical conclusion, internal, construct and external validity perspectives. The aim is to seek the fundamental notion of finding weaknesses and then reaching validity statements. Since the publications of this thesis use theory and experimental data collection, the reliability of the findings are also incorporated into the statistical conclusion validity. Hence, the following represent the validity assessment of the results of this thesis.

- *Statistical conclusion validity & reliability*

In the project-driven publications of this thesis, all data collection methods are separated from the project or workpiece requirements. Moreover, the relevant project input is described transparently so that the connection between results and input can be clearly investigated by external parties. In theory-driven publications, the experimental procedure is illustrated explicitly. The input to experiments, whether describing a production system or disturbance, is presented for repeatability.

- *Internal validity*

For publications that deploy experimental data collection, the main sources of internal validity threats are identified as the influences of the experimenter, measurement errors and pre-conditioned case selection. The aim is to minimise the first threat, experimenter influence, by exposing the experimenter to new technologies within the feasible limits of this thesis, thus avoiding rule-of-thumb conclusions. In Publications A, B, C and D, different technologies are subjected to design investigation. Publications E, F and G use simulation and different PKMs respectively, as the subject of the experiments and development. Although Publication F uses the technology of Publications B and C, the technology investigated is not related to design but active control. The second threat, incorrect measurements, is dealt with by interpreting the results based on their relativity to the input. Thus, all publications in this thesis strictly avoid using absolute data to reach conclusions. The third threat, pre-conditioned case selection, is mitigated by choosing cases in which a control group (dedicated fixtures) is proven to be functioning. This means that applying flexible fixtures in project-driven publications is evaluated experimentally in cases that are conditioned to the control group.

- *Construct validity*

The five criteria and their constituent elements in this thesis are the results of iterative theory advancement. A chain of evidence is not only established by the preceding state; the chain is also distributed across different cases and industries, which form a set of differing data sources. This bears similarity to the concept of triangulation. Operationalisation of the constructs (by using metrics) is realised via relative measurement techniques, in which relativity is associated with the production system being studied. Similarly, the constructs for active fixture control are evaluated directly in respect of the state-of-the-art. Their relative weaknesses are also discussed in each publication, for evaluation by external parties.

- *External validity*

The external validity of the results presented in this thesis is investigated based on the sources of data collection and types of processes which form the basis of experimentation. This means relative boundaries can be determined, based on where the results show the greatest external validity. From a data collection point of view, the publications use data from the automotive and aerospace industries. Thus, a respective boundary can be established based on their characteristics; automotive as typical mass production and aerospace as more inclined towards customisation. Thus, the first statement regarding the external validity of this thesis can be formulated as follows: an external validity threat to this thesis exists in production systems where greater customisation is needed. The second perspective addresses the processes at which the studied flexible fixtures are aimed. In Publications A and D, spot welding assemblies are studied, while Publications B and C study the assembly of aerospace components, covering assembly processes that involve drilling and sealant applications. In Publication F, a more process-independent strategy is used to expand the external validity of this thesis. However, the commonality among these processes (that they use, relatively speaking, larger and heavier workpieces) constitutes a threat. Consequently, a threat formulation may be realised as follows: the processes operating on small-scale workpieces compared to the automotive and aerospace industries (as is commonly observed in machining) may not show coherence with the constructs of this thesis.

A final discussion may be held in relation to the demand of the DRM's final stage, Descriptive Study II. In this thesis, a particular distinction is made regarding external evaluation of this stage under the stated delimitations. Naturally, the application of this thesis' results by external parties poses a threat to the validity of the results. However, this thesis sees this threat as future work; work which eventually leads to the findings being qualified as falsifiable artefacts. Consequently, the results presented remain consistent with the theoretical perspective of this thesis.

5.4 FUTURE WORK

This thesis does not include the newly emerging production system paradigms (such as cyber-physical systems), due to a lack of consensus and examples of application. However, the change is being implemented in the research phase of this work. Therefore, future work regarding the efficiency and design characteristics of flexible fixtures will be pursued for the emerging paradigms. As things stand, the application of active control in context of flexible fixtures will eventually require a new sub-criterion of quality, since the proposed metrics do not include the contribution of actively controlled flexible fixtures in terms process assurance.

Another path that the research on flexible fixtures may pursue is in active control of flexible fixtures in relation to non-rigid workpieces. This thesis considers only rigid workpieces; however, the relevant publication discusses the impact of such applications. Such endeavour may be valuable in expanding the use of flexible fixtures.

VI

CONCLUSIONS

In its pursuit of flexible fixturing efficiency, this thesis presented the efficiency of flexible fixtures from the perspectives of adaptation to manufacturing system characteristics, technological capacity, systematic design, and utilisation. A set of five criteria along with their sub-criteria and anticipated states has been given. These criteria encapsulate these perspectives and describe an efficient flexible fixture. The five criteria are initially described as: fundamental fixture, flexibility, cost, time and quality. The supporting sub-criteria that specifically address flexible fixture features can be summarised as follows:

1. Flexible fixture’s weight and size.
2. Flexible fixture’s capability to meet multiple workpiece and process physical demands.
3. Flexible fixture’s capability to be modularised through standardisation.
4. Flexible fixture’s capital and setup cost.
5. Flexible fixture’s capability to reconfigure or rebuild rapidly.
6. Flexible fixture’s capability to inform and actively contribute to process quality.
7. Flexible fixture’s capability to act in conjunction with remaining resources.
8. Flexible fixture’s reliability against malfunctions.

The determined criteria bridge the cost, time, flexibility and quality aspects of production systems to flexible fixtures. In so doing, the criteria are incorporated into a design procedure with relevant metrics, so that the use of the efficiency metrics can be systematically evaluated. The design procedure encapsulates both mechanical and control aspects of flexible fixtures in stages of conceptual and detailed design. In mechanical design, the conceptual design procedure focuses on the use of kinematic structures in respect of standard components, different actuation and position-holding choices. Aspects of control system component selection and controller software design are also given in the conceptual design of control systems. Initial efficiency is determined based on the weighting scheme adapted to a specific production system. The detailed design and analysis stages finalise the developed fixture and draw conclusions as to efficiency. Furthermore, a novel translational parallel kinematics machine is developed to show the applicability of the design procedure in relation to mechanical analysis.

General active control strategies are presented, to advance the use of the design procedure and increase the overall efficiency of flexible fixtures. The presented control strategies advance the capabilities of flexible fixtures by regulating the process parameters via force and position control. A Hilbert transform-based controller is presented in position control. Hence, the regulation of a flexible fixture’s position is elaborated to handle both oscillatory and non-periodic disturbances. In force control, direct and indirect control strategies are presented for single and system of flexible fixtures. Through the developed active control strategies, the use of flexible fixtures for disturbance-handling is advanced in various processes and exemplified via experiments.

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